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RECOMMENDED PROCEDURES FOR MEASURING AIRCRAFT
NOISE AND ASSOCIATED PARAMETERS

By

Alan H. Marsh

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RECOMMENDED PROCEDURES FOR MEASURING AIRCRAFT NOISE AND ASSOCIATED PARAMETERS

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SUMMARY

Experimental values of aircraft flyover noise levels (and associated parameters) are required to satisfy various needs of the NASA Aircraft Noise Prediction Program. Specific recommendations are made for test criteria, instrumentation performance requirements, data-acquisition procedures, and test operations. The recommendations are based on state-of-the-art measurement capabilities available in 1976 and are consistent with the measurement objectives of the NASA Aircraft Noise Prediction Program. The recommendations are applicable to measurements of the noise produced by an airplane flying subsonically over (or past) microphones located near the surface of the ground. Aircraft types covered by the recommendations are fixed-wing airplanes powered by turbojet or turbofan engines and using conventional aerodynamic means for takeoff and landing. Recommendations for data processing, analysis, and reporting are not included in the report. Various assumptions with respect to subsequent data processing and analysis were made (and are described) and the recommended measurement procedures are compatible with the assumptions. Some areas where additional research is needed relative to aircraft flyover noise-measurement techniques are also discussed.

INTRODUCTION

In 1974, the NASA Aircraft Noise Prediction Office (ANOPO) commissioned an initial series of Key Technology Documents (KTD) describing methods to predict the strength and directivity of various aircraft noise sources; a KTD describing atmospheric propagation effects was also prepared (see refs. 1 and 2). Furthermore, as part of an interim noise-prediction capability, ANOPO acquired methods and the corresponding data

bases for computing noise exposure contours around airports, specifically the NOISEMAP program developed by Bolt Beranek and Newman Inc. (BBN) for the United States Air Force (USAF) (refs. 3 and 4), and the Noise Exposure Forecast (NEF) contour calculation method developed by Wyle Laboratories for the United States Department of Transportation (ref. 5). ANOPO also has available the extensive data base of noise and airplane-performance information prepared by The Boeing Company, McDonnell Douglas Corporation, and Lockheed Aircraft Corporation for the Federal Aviation Administration (FAA) for current jet-powered air-carrier airplanes (refs. 6 to 8).

The empirical data now used by ANOPO as part of the interim noise-prediction capability were obtained by various organizations employing a wide range of data-acquisition and data-processing procedures for laboratory tests, full-scale static engine tests, and airplane flyover noise tests. The methods used to acquire the aircraft flyover noise data probably have the most variability because of the evolving state-of-the-art in flyover noise measurement technology and because of the proprietary aspects of flyover noise test programs oriented toward engineering research or aircraft noise certification.

As part of the ANOPO plan for review and updating the documentation of various technical aspects of the NASA Aircraft Noise Prediction Program (ANOPP), NASA initiated preparation of several Round II KTDs in 1976. Because of the variety of test procedures used to obtain the existing aircraft noise data base and because of a need to define test procedures to be used in future NASA programs for obtaining additional test data to verify models for the prediction and propagation of aircraft noise, one of the first efforts in the Round II activity was preparation of a document establishing recommended state-of-the-art procedures for aircraft flyover noise measurements.

This report recommends procedures to be used when conducting future aircraft flyover noise tests in support of ANOPO objectives. The report begins with a statement of the intended use of the test results, reviews most of the relevant documented measurement procedures, and describes the assumptions that were made for subsequent data processing and analysis. The purpose, scope, applicability, and measurement objectives for the

report are explicitly stated. The main part of the report covers four topics: test criteria, instrumentation performance requirements, data-acquisition procedures, and test operations. Recommendations for areas of additional needed research with respect to aircraft flyover noise measurements and a list of symbols are given in Appendixes A and D, respectively.

ANOPO REQUIREMENTS FOR FLYOVER NOISE TESTS

Results of aircraft flyover noise tests conducted using the procedures recommended herein are intended to be used for the research purposes of developing and validating the aircraft noise prediction methods of ANOPO. ANOPO has several different requirements for flyover noise test data. These requirements include, but are not necessarily limited to: (1) development of a consistent and accurate base of noise and aircraft-performance information for use in generating noise-level and noise-exposure contours around airports, (2) evaluation of forward-motion and ground-reflection effects predicted for various aircraft noise sources, (3) validation of individual component-noise-source prediction methods as well as proposed methods for combining the component predictions into a prediction of the total noise produced by an airplane during actual takeoff or landing operations, (4) validation and improvement of analytical models for predicting propagation effects along the sound path from an aircraft to a location under or to the side of the flight path, and (5) verification of various noise-reduction prediction techniques. The noise-reduction techniques include jet noise suppression systems and acoustically absorptive linings in inlets and exhaust ducts. References 1 and 2 provide further details on ANOPO requirements for flyover noise test data.

EXISTING MEASUREMENT PROCEDURES

Flyover noise tests are conducted for one of five purposes: research, development, certification, surveys, and monitoring. Aircraft noise certification tests are highly structured with detailed rules published in various documents. Surveys of noise levels around airports are performed for a variety of reasons using test procedures that are highly variable. Airport noise monitoring is performed by various organizations and usually for

local airport proprietors for nonscientific objectives with test procedures appropriate to the local airport situation.

Research and development flyover noise testing falls into two classifications: uncontrolled and controlled. Uncontrolled testing may have scientific objectives, but atmospheric conditions, engine power settings, aircraft configurations, and flight paths are usually not coordinated with or controlled by acoustical test personnel. Controlled tests are conducted only for a scientific or engineering purpose and have close coordination among acoustical test personnel, meteorologists, aircraft tracking crew, and the flight crew.

The distinction between research tests and development tests is that flyover noise research tests are conducted by aircraft manufacturers or government agencies for various scientific or engineering objectives under either uncontrolled or controlled conditions. Flyover noise development tests, however, are conducted by aircraft manufacturers prior to aircraft noise certification tests to evaluate the acoustical performance of various alternative configurations of noise reduction systems. Development tests are usually conducted under controlled conditions.

The subject of this report is data acquisition for controlled research tests. There is little published documentation on procedures currently used for controlled research tests conducted either by government agencies or by industry. Most of the existing documents describing aircraft flyover noise test procedures were developed for noise certification tests or to acquire general measurements of aircraft noise or general acoustical data base information. Moreover, most of the existing documents were in the process of being revised at the time of preparing this report.

References 9 and 10 describe procedures used in 1969 for flyover noise research tests. Reference 11 reviews the 1969 tests conducted by The Boeing Company and also some tests conducted in 1970 using a 747 aircraft. Reference 12 describes flyover noise research tests conducted by Douglas Aircraft Company with refanned JT8D engines on a DC-9-31 airplane in January and February 1975. The procedures recommended in this report are consistent with the state of the art as described in reference 9 to 12 and with procedures used by the NASA and the FAA in conducting flyover noise research tests.

There are at least nine existing documents prescribing methods to be used for measuring aircraft flyover noise. The procedures in reference 13 were developed by Committee A-21 of the Society of Automotive Engineers (SAE) in 1964, but are now inadequate and obsolete. At the time of preparing this report, a subcommittee of Committee A-21 was in the process of developing a revised version of reference 13 to incorporate more specific details and to reflect more current practices of the aircraft industry. In 1964 and 1965, the International Standards Organization (ISO) developed a document that was subsequently issued in October 1966 and then revised and reissued in June 1970 (ref. 14) describing test procedures applicable to obtaining a description of noise levels around in airport. A companion ISO document was also issued in 1970 (ref. 15) to describe procedures for monitoring of noise during takeoff and landing operations. A Working Group under Subcommittee 1 of ISO Technical Committee 43 for Acoustics has been working since 1973 on another revision combining references 14 and 15 and has produced a Draft International Standard (ref. 16).

The concept of federal certification of the noise produced by an aircraft of a given design became a part of the design requirements for U.S. transport aircraft when Part 36 of the Federal Aviation Regulations (FAR 36) was promulgated by the FAA in December 1969 (ref. 17). The FAR 36 requirements contain specific procedures and limitations for flyover noise tests to be conducted to demonstrate compliance with maximum noise levels allowed under specific conditions. Essentially these same procedures and requirements were adopted in April 1971 by the International Civil Aviation Organization (ICAO) and incorporated as International Standards and Recommended Practices in Annex 16 to the Convention on International Civil Aviation (ref. 18).

At a meeting in Montreal, Quebec in January and February 1975, the ICAO Committee on Aircraft Noise recognized the need to consider various technical changes to ICAO Annex 16 as well as changes to the conditions and the stringency of the requirements (ref. 19).

In support of the ICAO Annex 16 revision activities and the work of the ISO subcommittee preparing reference 16, a technical committee of the International Electrotechnical Commission prepared a document describing electroacoustical performance requirements for instruments used for measuring aircraft flyover noise (ref. 20).

The United States Environmental Protection Agency (EPA) has developed and published several proposed new aircraft noise regulations. In conjunction with the development of these regulations, the EPA contracted with BBN to apply methods developed for the USAF (refs. 21 and 22) and to develop a data base for civil aircraft (ref. 23). The data base incorporated judgments derived from BBN's experience in the measurement and analysis of the noise produced by various kinds of aircraft and differs from the corresponding data base produced by the aircraft manufacturers (refs. 6 to 8). EPA also contracted with BBN to review the technical aspects of Appendixes A, B, and C of FAR 36 and to recommend appropriate modifications (ref. 24).

The USAF is involved in a comprehensive program to acquire flyover noise data on operational and future military aircraft. The procedures used to acquire the flyover noise data are described in reference 25. These procedures are similar to those used for aircraft noise certification testing, but modified to be consistent with USAF requirements for predicting airport community noise levels.

The recommended procedures contained in this report were developed considering current practice and the material contained in the above-mentioned national and international documents.

ASSUMPTIONS FOR DATA PROCESSING AND ANALYSIS

The structure of a test plan for data acquisition depends in large measure on the data-processing procedures that will be used, the data-analysis techniques that will be employed, and the data-reporting requirements; that is, on the total test objectives and the procedures for data handling and analyzing. It was assumed for the purposes of this report that the data-acquisition and data-processing systems would be planned to function together as a single entity (though rather elaborate and sophisticated). The major assumptions are described below.

Test Site and Flight Paths

It was assumed that the tests would be conducted in the vicinity of a runway of suitable length and equipped with appropriate tracking, meteorological, and navigation aids. It was assumed that the tests would be conducted

with straight (or essentially straight) flight tracks for the duration of each flyover noise recording. It was assumed that it would not be a purpose of an ANOPO test program to evaluate acoustical effects associated with curved or banking maneuvers during takeoff or approach. It was also assumed that it would not be a test purpose during any given flyover noise recording to evaluate the acoustical effects of changing engine power setting or aircraft configuration. Thus, although the test criteria, instrumentation, and many of the recommended procedures would still be applicable, the test operations would have to be modified to accommodate thrust cutbacks during climbout and flap-management schedules and two-segment glide slopes during landing approach. The study of noise produced during transient engine operations may well be a legitimate research objective for NASA, but is not felt to be within the scope of flyover noise tests conducted for ANOPO.

Data-Processing Equipment

It was assumed that processing of the information acquired in the field would be accomplished in a specially equipped laboratory. Data reduction would be performed using automatic (or semiautomatic) procedures. The services of a qualified calibration laboratory would be available to support the total effort of data acquisition and data processing.

A large-memory, high-speed digital computer was assumed to be available to perform all the required calculations and to determine statistical measures of the validity of the results.

No direct data links between a field station and a data-processing laboratory and no on-line data processing were considered to be required for the purposes of ANOPO test programs. A strip-chart level recorder and other suitable instruments should be available in the field, however, for monitoring the aircraft noise signals and the ambient noise levels and to determine the cutoff times for the acoustic data recordings.

Basic Noise Data

It was assumed that the data to be produced would consist of 1/3-octave-band sound pressure levels as a function of frequency and time, as measured at each microphone location, throughout the duration of each aircraft flyover.

It was assumed that all sound pressure levels would be corrected for deviations from nonflat frequency response and for the presence of interfering ambient noise. "Duration" here was assumed to mean from the time the aircraft noise signal first reached an ambient threshold level (i.e., some finite amount, say by 5 dB, above the ambient noise level) to the time of final decrease of the signal to the ambient threshold. This definition would apply to every 1/3-octave band with geometric mean frequencies from 50 to 10 000 hertz (Hz). The longest duration will generally be associated with one of the 1/3-octave bands below 500 Hz.

The sound pressure levels would need to be known at regular, discrete instants of time throughout the duration. The time interval between data samples was assumed to be on the order of 0.5 seconds. It was assumed that the total test system would be planned with a required accuracy of ± 1.0 dB, or less, for the measured sound pressure level data, and with a required accuracy of ± 0.01 second, or less, for the corresponding time identification.

Associated Parameters

The basic sound pressure level data were assumed to be accompanied at every instant of time by appropriate information on airplane location (in x, y, and z coordinates of a reference point on the airplane, given the x, y, and z coordinates of each microphone and the location of some benchmark on the ground for reference). Coordinates x and y would be in the ground plane (a plane containing the ground reference benchmark) with the x direction in the direction of the extended runway centerline, the y direction perpendicular to the extended runway centerline. The z coordinate indicates height above the extended runway centerline. The required accuracy of the measurements of the distance between each microphone and the airplane reference point was assumed to be ± 10 percent, or less. In addition to the aircraft position data, it was assumed that the basic sound pressure level data would be accompanied by information on airplane configuration (flap setting, location of high-lift devices, and position of landing gear), on airplane flight status (true airspeed, fuselage attitude, and weight), and on the power setting of the engine(s) as well as a description of their acoustical configuration.

It was assumed also that the basic sound pressure level data would be accompanied by time-correlated measurements of appropriate meteorological data. The meteorological data would be required for determining adjustments between test-day (as measured) conditions and some established reference meteorological conditions. The adjustments would be applied to the basic measured sound pressure levels and to the strength of the engine's noise sources. The sound pressure level adjustments would account for differences in atmospheric absorption along appropriate acoustic propagation paths as well as ground reflection effects, for each 1/3-octave band and at each instant of time, taking into consideration acoustic propagation times along the paths and Doppler frequency shifts.

Anticipated Reference Conditions

In addition to data adjustments for the effects of nonreference meteorological conditions, it was expected that adjustments would be required to normalize the basic data to a reference flight path, reference airspeed, reference engine power setting, and reference aircraft configuration. Except for the meteorological data, all of the reference conditions would have to be selected appropriate for the aircraft and engine being tested. The reference parameters for the basic noise data were assumed to be referred net thrust (F_n / δ_{am}) and referred fan speed ($N_1 / \sqrt{\theta_{t2}}$), where δ_{am} is the ratio of the ambient pressure around the aircraft to the standard atmospheric pressure of $1.01325 \times 10^5 \text{ N} \cdot \text{m}^{-2}$ ($2116 \text{ lb} \cdot \text{ft}^{-2}$) and θ_{t2} is the ratio of the total temperature at the inlet to the fan (of a turbofan engine) to the standard air temperature of $288.15^\circ \text{ kelvin}$.

Meteorological reference conditions appropriate for processing all aircraft flyover noise data would be established before conducting any tests. Establishment of reference meteorological conditions would be required to plan the flyover noise tests. The test criteria would then be selected so as to minimize the magnitude of the resulting data adjustments due to deviations from reference meteorological conditions.

For purposes of test planning, it was assumed that the reference conditions would be:

- (1) no wind
- (2) runway at sea level

- (3) atmospheric pressure at the surface equal to $1.01325 \times 10^5 \text{ N.m}^2$
(or one standard atmosphere, ref. 26)
- (4) air temperature at the surface equal to $298.15^\circ \text{ kelvin}$ (25° celsius
or $77^\circ \text{ fahrenheit}$)
- (5) standard temperature lapse rate with height above the surface
(see ref. 26)
- (6) relative humidity of the air at the surface equal to 70 percent
- (7) standard lapse rate for the relative humidity with height above
the surface (see ref. 27)

It was assumed that the reference surface was at a height of 10 meters (10 m) above ground level.

Although not exactly a reference condition, the assumption was made also that the tests would be conducted in an environment with minimal ambient noise using equipment having minimal background electrical noise.

Derived Noise Measures

The basic noise data would be adjusted for the presence of interfering ambient noise levels, nonflat free-field frequency response, and the effect of the windscreens. It was then assumed that the adjusted data would be used to calculate various summary-type noise measures, such as A-weighted sound pressure level, tone-corrected A-weighted sound pressure level, perceived noise level, tone-corrected perceived noise level, and effective perceived noise level. The tone corrections would apply only to true tonal components of the received sound signal and not to spectral irregularities introduced by ground reflection effects or atmospheric absorption. (Current algorithms for computing tone-correction penalties, for example those in reference 17, can assign tone-corrections to spectra having sharply falling high-frequency sound pressure levels caused by atmospheric absorption effects.)

PURPOSE

The purpose of the report is to describe recommended data-acquisition test procedures for measuring aircraft flyover noise levels and associated parameters for various types of airplanes in various geographical locations.

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SCOPE

The scope of the report is limited to recommended procedures for acquisition of test data. The end result of following the recommended procedures are records that can be used in subsequent data processing and engineering analysis efforts.

APPLICABILITY

The recommended data-acquisition procedures are applicable to measurements of the noise produced by an airplane flying subsonically over (or past) a microphone (or several microphones) located outdoors and above the surface of the ground. The procedures are applicable to fixed-wing airplanes (regardless of weight) powered by turbojet or turbofan engines (regardless of bypass ratio) and using conventional aerodynamic means for takeoff and landing, but without afterburning (or duct burning) in the engine's exhaust nozzles. The procedures include those for measurement of the noise produced by an airplane's engines, but not the noise produced by the motion of an airplane through the air with the engines not operating (that is, by nonpropulsive noise sources). The procedures are not applicable to measurements of the noise produced by an airplane on the ground (e.g., noise produced at the start of or during takeoff, noise produced by reverse-thrust operations during landing, or noise produced during ground runup).

MEASUREMENT OBJECTIVE

The objective of the tests is to determine 1/3-octave-band sound pressure levels as a function of time as the aircraft flies over (or past) the microphone(s). The nominal geometric mean frequencies (center frequencies) of the 1/3-octave bands range from 50 to 10 000 Hz with nominal center frequency values as specified in reference 28. Sound pressure levels are in decibels (dB) with a reference acoustical pressure of 20 micropascals (20 μ Pa) (ref. 29).

OVERVIEW OF RECOMMENDED TEST PROCEDURES

The recommended test procedures described below were developed in consideration of the stated objectives of the NASA Aircraft Noise Prediction Program, the intended uses of the test results, and the various assumptions that were made regarding data processing and data analysis. It was apparent that acquisition of acoustical data in the field would require recording on an instrumentation-grade multiple-channel magnetic tape recorder. The ratio of the level of the flyover noise signal to the level of the electrical background noise in the total data-gathering system would have to be high. The dynamic range of the recording system must be capable of handling a wide range of signal levels. The ambient noise level should be as low as feasible. Furthermore, the sound pressure levels should be recorded in an environment where ground reflection effects do not introduce significant spectral irregularities at any frequency in the range of interest, i. e., such that the sound pressure levels are a uniform 3 dB above the corresponding free field values.

It was felt that the tests should yield free-field sound pressure levels because all the source noise-prediction schemes developed to date (see list in reference 2) provide estimates of free-field sound pressure levels. Measurement of free-field sound pressure levels would also avoid the highly variable ground plane absorption and reflection effects and would eliminate the need to account for reflection-induced pseudotones in subsequent data analysis.

The test procedures recommended here involve a series of nominally level flights over an array of microphones. The microphones are placed under and to each side of the nominal flight path. The microphones are installed on supporting stands at a height above the ground that is large enough to ensure that ground-reflection effects occur at frequencies below the frequency range of the 50-Hz 1/3-octave-band filter throughout most of the flyover noise recording.

The test airplane flies a predetermined flight path with preselected airspeed, configuration, weight, engine power setting, and height above ground level. The tests are repeated a number of times to obtain data for a

range of heights, airspeeds, engine power settings, and configurations. Airplane position, meteorological data (at the surface and aloft), airplane data, and engine data are all measured and time-synchronized with the sound pressure level recordings.

The next four sections set out specific recommendations for test criteria, instrumentation performance requirements, data-acquisition procedures, and test operations.

RECOMMENDED TEST CRITERIA

While it may be technically feasible to conduct flyover noise tests at many different locations and under whatever meteorological conditions that might exist at any given time, it is necessary to place certain restrictions on the test site and weather conditions in order to assure the intercomparability, accuracy, and reproducibility of the test results. Moreover, at the present, there are no reliable methods to account for some phenomena that occur during the generation and propagation of sound from an aircraft to a microphone located near the ground. Thus, it is necessary to restrict the range of certain conditions so that the tests are conducted under conditions that permit the subsequent data analyses to account for those propagation effects that are considered to be understood (e.g., inverse-square diminution of the sound pressure with distance in the far field of acoustic sources and atmospheric absorption of sound energy during propagation through a still, homogeneous atmosphere).

The test criteria described here are for three factors considered most critical for successful flyover noise test programs: namely, characteristics of the test site, ambient noise levels, and meteorological conditions. The recommended test criteria reflect the state of the art in measuring aircraft flyover noise. Improved test criteria will require additional research, especially in the areas of atmospheric attenuation, propagation at long distances and in directions other than directly below the flight path, and ground reflections, as described in items 1 to 4 of Appendix A.

Test Site Characteristics

Measurement of aircraft flyover noise levels for engineering research and development purposes began in the early 1950s. For many years, relatively little concern was given to the characteristics of the test site since most tests were conducted with "target-of-opportunity" airplanes. Some tests were even conducted over water with a microphone installed on a boat.

Since the mid-1960s, more and more attention has been given to the selection of a test site, especially for noise certification tests conducted since 1970. In order to improve the intercomparability of test results, test site requirements have become more restrictive and an area of controversy because the cost of conducting tests increases rapidly as the specifications become more restrictive.

An ideal test site might be one with a long, level runway with a sea-level elevation and surrounded by smooth, flat, treeless, unvarying terrain for several kilometers in any direction. There would be no interfering air traffic (or very little) and no restrictions on airplane maneuvering or operations.

The test site would be usable 24 hours per day and any day of the year. The winds would be generally calm. There would be little or no precipitation of any kind, and no fog or low clouds. The pressure, temperature, and humidity would always be close to the reference values.

Vegetation, if any, in the region of the site would be quite sparse and would not exhibit marked changes during different seasons of the year.

Access to the microphone locations would not require any special vehicles or need any special permissions from local land owners (or land users).

Ambient noise levels would be minimal, with no interfering noise from other airplanes, highways, farming equipment, or even animals, birds, or insects.

In practice, of course, the selection of a test site is a compromise among the above considerations. The chief factors involved in the decision are the temperature and humidity of the air (and their vertical distributions) and the wind. Ambient noise levels can usually be accommodated or a run can be repeated if some unusual sound was recorded. Other factors (such as

servicing, airplane traffic, flight pattern restrictions, distance from a home location, access, weather fronts, storms, and airport neighbors) can usually be overcome with an impact on test schedule and program cost.

The effects of the terrain and ground cover on measurements of the noise levels and weather parameters can be substantial. If a microphone is located only a short distance above ground level (say 1.2 m), then the noise levels in much of the lower part of the frequency range of interest will have contributions from both the direct signal from the airplane and a signal reflected off the surface of the ground. The magnitude and phase of the reflected signal depend on the nature of the terrain, i. e., on its acoustical impedance. Different reflection effects will be obtained if the surface is hard and quite reflective (e. g., concrete, asphalt, or dry, sun-baked adobe clay), or absorptive (e. g., grass with the absorptivity depending on the length of the grass, season of the year, and whether the soil and grass are dry or damp; or dirt that has been rototilled, freshly plowed, spaded, or is loose sand). The magnitude of the reflection differences between hard and absorptive surfaces has not been quantified for 1/3-octave-band sound pressure levels from aircraft noise.

Placing the microphone on, or flush with, the surface (say on an asphalt or plywood surface) effectively eliminates spectral irregularities caused by reflection effects, but introduces variability in the resulting data caused by temperature gradients and turbulence near the surface, especially for frequencies above 1000 Hz. For surface or flush installations it is difficult also to determine proper microphone frequency-response corrections for different angles of incidence (at different times during a flyover); incorporation of a windscreen over a surface-mounted microphone further aggravates the problem of determining proper frequency response corrections for various angles of incidence.

Placing the microphone on a stand or support at a considerable distance above the ground has several advantages. Spectral irregularities caused by ground reflection effects occur at frequencies below the frequency region of interest for most incidence angles. Variations caused by different types of terrain or ground cover are eliminated, thereby increasing the number of options for a suitable test site since terrain and ground cover would no longer be important factors. The main disadvantage of locating the microphones at

large heights to measure sound pressure levels that are essentially 3 dB higher than comparable free-field values is the requirement to use some type of portable tower (rather than a simple tripod) to support the microphone, preamplifier, and cable. Extra effort is needed to set up the microphones and to calibrate and check out the data-acquisition system. The advantages in improved data reliability and test site flexibility should outweigh the disadvantages.

Thus, it is recommended that the test site have the following characteristics:

General location. - The test site should be at an airport equipped with navigation aids and an air traffic controller. The airport should have as little local traffic as possible. The airport should have at least one runway suitable for takeoff and landing operations at the heaviest operational weights applicable to the test airplane. The runway should be as level as possible with a slope of no more than 3 m in a length of 2 km. The runway elevation should be no more than 600 m above mean sea level, and preferably no more than 300 m. (Item 6 in Appendix A discusses the need for additional study to evaluate the effects of runway elevation.)

Terrain. - The terrain on both sides and off both ends of the test runway should not have mountains or hills that would interfere with the maneuvering of the airplane or produce reflections in the aircraft noise recordings. The terrain around the microphones should be approximately flat and level with the runway with a slope of no more than ± 30 m in 1 km (2 degrees) in any direction for a distance of at least 2 km. There should be no large bodies of water (ponds, lakes, reservoirs, or oceans) near the microphone locations. The nature of the ground cover around the microphones is not important so long as it is not too unusual (e.g., extensive shrubs and bushes; fresh and deeply plowed ground; fields of tall grasses such as wheat, alfalfa, or corn; orchards; vineyards; and vegetable fields should all be avoided). The moisture content of the soil around the microphones is also not too important so long as the microphones and surface weather stations are mounted at the recommended height.

Obstructions. - Obstructions and large reflecting objects or structures must not be present behind the microphones or between the aircraft's flight path and the line-of-sight to the microphones. Obstructions between the aircraft and the microphones can cause shadowing and spectral distortions in the received sound signal. Reflections from objects behind the microphones can also introduce unwanted spectral effects.

Items that can act as obstructions or reflecting objects consist of trees, buildings, water storage tanks or towers, hills, large trucks or vans, and other similar objects. Personnel involved in the test also constitute reflecting objects and should not be near the microphones when the aircraft noise signal is being recorded.

In addition to the requirement to have an essentially free acoustic field for the sound to propagate through to each microphone throughout the duration of each noise recording for each test flight, it is also necessary for the airplane-tracking crew to be able to track the test airplane as it enters and departs the test area. An obstruction-free zone is recommended that extends horizontally 10 km in any direction from the test site and from the vertical down to 10 deg above the ground plane at the location of the airplane tracking facility.

Weather. - In addition to the physical constraints described above, it is mandatory to consider average diurnal and seasonal weather conditions existing at potential test sites. In this regard, experience has shown that it is desirable to have alternative test sites in addition to a primary test site so that test operations can be moved if necessary to a site forecast as able to meet the meteorological requirements.

Sites should be avoided that have many days with rain, snow, sleet, or hail, or that have many days with poor visibility because of fog or low clouds. Sites should also be avoided where the atmospheric conditions are stable for less than a few days at a time due to the periodic passage of weather fronts. Sites should also be avoided that have regular and strong inversions of the normal temperature-height profile that persist for several hours for many days each year.

Sites located near large bodies of water have regular daily patterns of on-shore and off-shore breezes. The on-shore winds increase in strength from the morning to the afternoon as the earth is heated by the sun; off-shore winds occur in the evening as the land cools. Winds (and atmospheric turbulence) usually occur before, and especially after, the passage of a frontal system through the test area.

Winds (at the surface and aloft) cause special problems in the measurement of aircraft flyover noise. Wind-induced turbulence can cause large fluctuations in the amplitude of the received sound signal. Winds and turbulence also make it difficult for the pilot to fly along the desired flight path or to maintain the desired flight speed (within the specified tolerance limits). Winds can also cause significant variations in both the horizontal and vertical distributions of temperature and humidity. Special attention therefore should be given to choosing test sites that can satisfy the desired wind limitations, for at least several hours a day for most of the days during the year, when the site also satisfies the temperature and humidity constraints.

Ambient Noise Levels

Ambient noise level is the noise level indicated by the data-acquisition/data-processing system in the absence of any aircraft noise signal. This definition includes electrical background noise.

Once a test is underway there is little that can be done to reduce the ambient noise levels. Therefore, it is recommended that sound level surveys be made, prior to conducting any tests, in the area around candidate test sites to assess the prevailing level of intermittent and steady-state ambient noise at different times of the day on various days of the year. A precision sound-level meter (one meeting the Type 1 specifications of reference 30) should be used for the surveys. Measurements should be made with the microphone 1.5 to 2 m above the ground. Values should be obtained for both linear (no frequency weighting) and A-weighted sound pressure levels.

It is recommended that the linear sound pressure levels be no more than 70 dB (preferably no more than 60 dB) and that the A-weighted sound pressure levels be no more than 55 dB (and preferably no more than 45 dB). There should be at least a 15-dB difference between the linear and the

A-weighted sound pressure levels. All measurements should be taken with high meter damping (slow scale) and averaged over several seconds to obtain the average of the maximum and minimum sound levels present at the time in accordance with the recommended procedures in section 8 of reference 31. The values of linear and A-weighted sound pressure levels are consistent with those noted in previous flyover noise tests, refs. 9 and 32. The recommended values for A-weighted sound pressure levels are also consistent with those reported in reference 33 for rural areas with little or no traffic noise and during daytime hours. Somewhat lower values would be expected at night, perhaps a mean value of 40 dB in a rural area away from traffic.

There should be no discrete-frequency tones audible to the person making the measurement (assuming he has normal hearing acuity). In particular, there should be no tones at 60 Hz, or higher harmonics, radiated from nearby electrical power transformers and no audible tones due to wind-induced vortices shed from electrical power lines or telephone wires.

If ambient noise level surveys show that the candidate test site meets the recommended criteria, and if the ambient noise levels during a test do not exceed the maximum recommended values, then there should be few problems with ambient noise interference throughout the range of engine power settings and microphone-to-airplane distances envisioned here for aircraft for which the recommended procedures are applicable.

Meteorological Conditions

More controversial than the specification of criteria for the characteristics of the test site is the specification of criteria for meteorological conditions, and for good reasons. Atmospheric propagation effects are complex and important. The understanding of the physical phenomena is not complete.

Atmospheric factors cause large fluctuations in the amplitude of the sound pressure, at a given point in space between the source and the receiver, and also cause large reductions in the mean acoustic energy carried by a sound wave as it propagates, especially at the higher frequencies. Propagation losses are a function of frequency, distance traveled, temperature, humidity, and pressure. Since most aircraft noise has a rather broadband spectrum

and is analyzed with constant-percentage-bandwidth filters, the spectral slope of the noise and the frequency-response characteristics of the filters must also be taken into account because they affect the apparent magnitude of the propagation loss.

Atmospheric absorption mechanisms have been studied for many years. The acoustical energy carried by a sound wave is reduced by so-called classical processes and by molecular resonance effects. Classical losses are a function, principally, of the viscosity and heat conductivity of the medium. Molecular losses are due mainly to vibrational resonances of oxygen, nitrogen, and water molecules.

As a result of a need to have a uniform method of adjusting measured aircraft flyover noise levels to common meteorological conditions, the SAE A-21 Committee organized an effort in 1962 to develop a procedure. An SAE Aerospace Recommended Practice was subsequently issued on 31 August 1964.

This document (SAE ARP 866) has been incorporated directly in various national and international regulations and standards (refs. 14, 16, 17, and 18) as the basis for defining the procedure for adjusting from test to reference conditions. The 1964 document was issued as a revised document in 1975 to provide equations for calculating atmospheric absorption coefficients, and to improve the quality of the figures (ref. 34). The current interim NASA ANOPP method of accounting for atmospheric absorption losses (ref. 35) is based on the revised SAE document (SAE ARP 866A).

With all the background and documentation, is there any reason to be concerned about the atmospheric absorption component of propagation losses? The answer to this question appears to be yes.

In 1971, Working Group S1-57 of the S1 Standards Committee on Acoustics of the American National Standards Institute (ANSI) was formed under the sponsorship of the Acoustical Society of America to look into the question of producing an American National Standard on atmospheric absorption. This effort was considered to be required because additional laboratory experimental data obtained since 1962 showed that the absorption coefficients predicted by the SAE procedure were not correct. Furthermore, the procedures recommended by the SAE method for determining the loss over a

propagation path and the method of accounting for the loss in a band of noise (knowing the loss coefficients for pure tones) were considered inappropriate. Although Working Group S1-57 has produced several draft documents, no ANSI Standard was published on atmospheric attenuation of sound in 1976.

This discussion does not mean that the procedures of SAE ARP 866A should be discarded. On the contrary, all previous attempts to apply the recommended procedures of ARP 866A to test data have shown that, on the average, the methods of ARP 866A work reasonably well. Most of these judgments, however, have relied on summary data (e.g., maximum perceived noise level or effective perceived noise level) and used only "surface" measurements of air temperature and humidity to represent conditions along the "propagation path". For more detailed studies, it is necessary to define meteorological conditions aloft and to be more specific about the definition of acoustic propagation path for each 1/3-octave band in the frequency range of interest, for each instant of time of interest.

A study reported by FAA personnel (ref. 36) used only the sound spectrum at the time of maximum tone-corrected perceived noise level (according to the rules of ref. 17). It showed that spectral adjustments from test to reference conditions were more reasonable for the cases examined when done using a "layered atmosphere" approach rather than by assuming the surface conditions applied throughout the propagation path. Thus, ignoring inverse-square propagation spreading losses, the adjustments were based on

$$L_{p, \text{adj}} = L_{p, \text{meas}} + \sum_{i=1}^j (a_i - a_{\text{ref}}) d_i \quad (1)$$

instead of the FAR 36 method with

$$L_{p, \text{adj}} = L_{p, \text{meas}} + (a - a_{\text{ref}}) d, \quad (2)$$

where $L_{p, \text{adj}}$ and $L_{p, \text{meas}}$ are the adjusted and measured sound pressure levels in decibels at the surface (in any 1/3-octave band), a , a_i , and a_{ref} are atmospheric absorption coefficients in $\text{dB} \cdot \text{m}^{-1}$ determined for 1/3-octave bands from SAE ARP 866A for test and reference conditions, and d or d_i is the propagation path length in meters.

For equation (1), the propagation path is broken into j segments with each segment occurring in a horizontal layer that is 30 m, or less, thick. For equation (2), there is only one absorption coefficient for the one propagation path length. The value of a in equation (2) would be determined from measurements of temperature and relative humidity at a height of 10 m at a location near the microphones, or at a nearby airport facility approved by the FAA and also usually at a height of 10 m above ground level.

The recommendation of the ANSI Working Group S1-57 for computing adjustments between measured and reference meteorological conditions for propagation losses of bands of noise under nonhomogeneous atmospheric conditions is shown in equations (3) and (4) for levels at a receiver location:

$$L_{p,adj} = L_{p,meas} + (\Delta L_{B,meas} - \Delta L_{B,ref}) \quad (3)$$

where

$$\Delta L_{B,meas} - \Delta L_{B,ref} = 10 \log_{10} \left\{ \left[\int_{f_1}^{f_2} p_{meas}^2(f) \tau(f) \times \exp \left(2 \int_{\xi_r}^{\xi_s} \alpha_{meas} d\xi \right) \times \exp \left(-2 \int_{\xi_s}^{\xi_r} \alpha_{ref} d\xi \right) df \right] / \int_{f_1}^{f_2} p_{meas}^2(f) \tau(f) df \right\} \quad (4)$$

The process indicated by equations (3) and (4) is equivalent to adjusting the received sound spectrum, in each frequency band for each instant of time, back to a source point (under measured meteorological conditions) and then computing the atmospheric absorption loss that the source sound spectrum would have encountered in propagating back along the same path to the receiver point (under reference meteorological conditions). Numerical integration techniques are required to evaluate equation (4). Inverse-square losses are ignored.

In equation (4), $\Delta L_{B, meas}$ and $\Delta L_{B, ref}$ are the band propagation losses, in decibels, under measured and reference meteorological conditions, respectively; $p_{meas}^2(f)$ is the power spectral density of the measured mean square sound pressure at the receiver, in $(N \cdot m^{-2})^2$; $\tau(f)$ is the nondimensional power transmissibility function for the frequency response of the actual filters used to obtain the band levels of the received sound spectrum; f_1 and f_2 are the lower and upper frequencies, respectively, defining the significant transmission of the filter for the received sound spectrum, in Hz; α_{meas} and α_{ref} are the pure-tone atmospheric sound attenuation constants, in nepers $\cdot m^{-1}$, for the measured and reference conditions, respectively; and ξ_r and ξ_s are the coordinates, in meters, of the receiver and source points, respectively. The atmospheric sound attenuation constant is a complex function of frequency, temperature, humidity, and pressure and would be determined, for a given frequency, for measured or the reference conditions along each propagation path.

If the atmosphere were homogeneous along the sound propagation path, then α_{meas} and α_{ref} would be constants, for a given frequency, and the integrals in the exponential terms could be replaced by $\exp(2 \alpha_{meas} \xi)$ and $\exp(-2 \alpha_{ref} \xi)$ and combined as $\exp[2(\alpha_{meas} - \alpha_{ref})\xi]$ where ξ is the length of the propagation path at each instant of time for which there are data.

It should be noted that SAE ARP 866 was developed with the best theoretical guidance and laboratory experiments available at the time and was confirmed in 1963, and reconfirmed in 1969, by an ad hoc subcommittee of the SAE A-21 Committee with best-available measurements of flyover noise levels and meteorological data. The data that were examined were the results of tests conducted by several organizations in different parts of the world.

The studies reported in references 11, 37, and 38 also examined various flyover noise measurements to extract atmospheric absorption coefficients. These studies all concluded that there was good agreement between experimentally derived absorption losses and those computed by the method of SAE ARP 866A, though severe signal-to-noise-ratio (dynamic range) problems in the higher frequencies limited the scope of the comparisons.

When the new procedures are approved by ANSI and evaluated in actual use, they should provide an improved method of determining pure-tone atmospheric absorption losses based on fundamental physical principles. Absorption losses for bands of noise will be determined differently than now done by the methods of SAE ARP 866A. The biggest difference will be in the procedures for determining the loss in a band of noise over a given propagation distance and adjusting from test to reference conditions. The consequence will be different procedures for analyzing the test results and different meteorological test criteria. A greater flexibility in the choice of test site and in the test operations should also derive from the new ANSI procedures. Eventually, it may be feasible to conduct tests at any convenient location under any existing conditions for temperature, humidity, and pressure (assuming negligible effects of wind and turbulence).

Unfortunately, the new procedures are not available and have not been exposed to any trial use. The procedures of SAE ARP 866A should be retained, therefore, until additional research has been conducted to evaluate improved procedures. (See item 1 of Appendix A.)

Temperature/humidity. - Figure 1 traces the historical development of temperature and relative humidity limits. Figure 1(a) shows the 1969 limits from refs. 17, 18, and 25, except that Annex 16, reference 18, permits tests to temperatures of 2° C (instead of 5° C as in FAR 36 or the BBN recommendation to AMRL). The temperatures and humidities in figure 1 (a) are measured at a height of 10 m above ground level. There is no requirement for measuring meteorological data above 10 m, except for the caveat that there is to be no temperature inversion that would significantly affect the noise level of the aircraft.

The rationale for choosing the temperature/humidity limits of figure 1 (a) was, first, the assumption that data measured at a height of 10 m would be representative of conditions along the sound propagation paths and, second, the desire to avoid those conditions where SAE ARP 866 predicted excessive atmospheric absorption losses and hence excessive adjustments to reference conditions (i. e., primarily at relative humidities less than 30 percent at low temperatures). The upper relative humidity limit of 90 percent was chosen to avoid humidity problems with the data-acquisition instruments (primarily arcing problems with the widely used air-dielectric capacitor microphones)

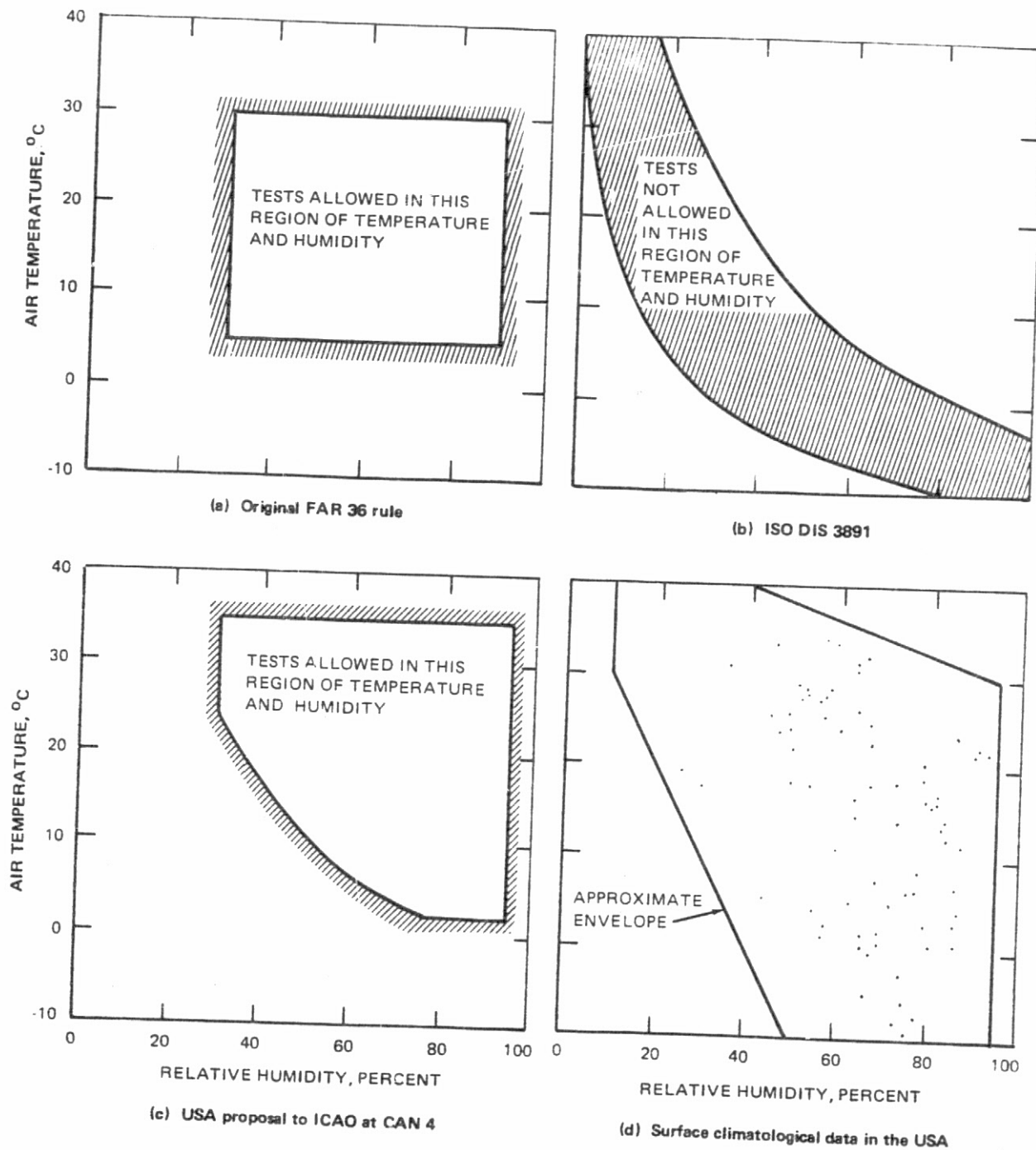


Figure 1. -Temperature/humidity limits.

and to help ensure that there would be no precipitation during the tests. The low temperature limit was also chosen to avoid instrumentation problems that have been noted at lower temperatures, as well as the human and operational problems accompanying below-freezing temperatures. The high-temperature limit was selected mostly to avoid the loss in engine takeoff performance (and consequent reduction in airplane climb capability) occurring when the temperature exceeds 30° C. These considerations are relevant still to tests conducted for ANOPO objectives.

Figure 1(b) shows the temperature/humidity limits adopted in 1974 by the Working Group preparing the draft ISO measurement standard for ICAO in support of the revision of ICAO Annex 16. The rationale here was to limit the magnitude of the absorption coefficient (determined by the method of SAE ARP 866A) to some value in a critical band. Since the higher frequency bands always have the largest absorption losses, it seemed reasonable to choose the band centered at 8 kHz because 8 kHz was the highest center frequency in the frequency range of interest for both an octave and a 1/3-octave band. A limitation of $10 \text{ dB} \cdot (100 \text{ m})^{-1}$ was selected to define the temperature and humidity limits. Given a reference atmospheric absorption coefficient of $4.9 \text{ dB} \cdot (100 \text{ m})^{-1}$ at 25° C and 70 percent relative humidity in the 8 kHz band and assuming equation (2) is valid, then the restrictions of figure 1(b) permit a 20.4 dB maximum adjustment in the 8-kHz band for a propagation distance of 600 m, a typical overhead distance for takeoff noise tests.

The new features of figure 1(b) were the inclusion of cold, dry conditions (lower left-hand part of the figure) and the requirement that the temperature and humidity were to be in the acceptable regions everywhere along all sound propagation paths between the aircraft and the microphone. This second requirement meant that meteorological measurements were required to heights at least equal to the aircraft's height in order to assure compliance. Also note that the practical limits on temperature or relative humidity in figure 1(a) were not included.

Figure 1(c) shows the compromise expanded proposal made by the USA delegation to the Fourth Meeting of the ICAO Committee on Aircraft Noise (CAN 4) in January and February 1975. This proposal adopted the upper boundary line from DIS 3891, figure 1(b), but added additional restrictions on temperature and relative humidity.

The upper temperature limit was increased to 35° C (95° F) from 30° C (86° F) of figure 1(a). The lower temperature limit was reduced to 2.2° C (36° F) from 5° C (41° F). The upper relative humidity limit was increased to 95 percent from 90 percent. The lower relative humidity limit was kept at 30 percent except where limited by the criterion of 10 dB · (100 m)⁻¹ in the 8 kHz band.

In addition to the new limits, the proposal required sampling of upper atmospheric meteorological conditions. The new limits, like those for figure 1(b), were intended to apply everywhere along all sound propagation paths from the test airplane to the microphones. If there were inversions of the normal lapse gradients for air temperature and relative humidity, then a layered-atmosphere analysis, equation (2), must be performed using layers that were no thicker than 30 m. Testing would be permitted with temperature inversions of as much as 9° C in 300 m (5° F in 1000 ft). Meteorological data, however, have to be measured from a height of 10 m to at least the height of the test airplane and at least as often as every 0.5 h during the test and must be interpolated to the actual time of the flyover noise recording. Local inversions can exceed the rate of 9° C in 300 m provided the layered-atmosphere analysis uses layers that are locally less than 30 m thick. Compared to the original FAR 36 requirement, the requirements and interpretations accompanying figure 1(c) add a cost burden, but probably provide more-representative sound pressure levels.

The omission of the option to test under cold, dry conditions is probably realistic as shown by the climatological data in figure 1(d). These data from reference 39 represent typical maximum and minimum values for the months of January and July for a sample of 22 cities in the USA, including Fairbanks, Alaska and Honolulu, Hawaii (see table 1). The only data omitted from figure 1(d) were the minimum January data for Fairbanks (-29.7° C at 68 percent) and International Falls (-22.3° C at 73 percent) and the maximum July data for Phoenix and Yuma, Arizona (40.3° C at 20 percent and 41.6° C at 23 percent). All data represent surface measurements and probably are for a height of about 1.5 m above the ground. (Note that the data in figure 1(d) represent typical maximum and minimum rather than extreme conditions; there were hotter and colder, and moister and drier days in reference 39).

TABLE 1. MAXIMUM AND MINIMUM TEMPERATURES
AND ASSOCIATED RELATIVE HUMIDITIES IN
VARIOUS LOCATIONS DURING 1972

LOCATION	JANUARY				JULY			
	DAILY TEMP (°C)		REL HUMIDITY (%)		DAILY TEMP (°C)		REL HUMIDITY (%)	
	MAX	MIN	MAX T	MIN T	MAX	MIN	MAX T	MIN T
ROCHESTER, NEW YORK	0.3	-7.9	66	73	28.1	15.9	53	81
DETROIT, MICHIGAN	0.7	-7.2	69	78	28.8	16.1	53	82
INT. FALL, MINNESOTA	-9.9	-22.3	68	73	25.8	11.6	57	87
PHOENIX, ARIZONA	17.8	1.8	30	66	40.3	23.9	20	47
JACKSON, MISSISSIPPI	14.6	3.0	64	86	33.8	22.1	60	93
MIAMI, FLORIDA	24.3	14.4	60	84	31.6	23.7	64	86
SAN DIEGO, CALIFORNIA	18.1	7.4	5.4	69	24.9	17.4	67	82
HARTFORD, CONNECTICUT	1.5	-8.2	57	72	29.4	16.6	51	80
CLEVELAND, OHIO	1.9	-5.9	69	75	28.0	16.3	57	82
SEATTLE, WASHINGTON	6.4	0.6	76	81	24.2	12.3	49	84
ATLANTA, GEORGIA	11.1	2.9	60	79	30.6	21.5	64	90
NEW ORLEANS, LOUISIANA	18.0	7.1	67	86	32.6	22.6	66	91
HOUSTON, TEXAS	17.3	4.2	64	87	34.2	21.8	57	93
YUMA, ARIZONA	19.3	4.4	26	55	41.6	25.9	23	49
LONG BEACH, CALIFORNIA	18.5	4.9	50	72	27.8	16.2	52	82
PORTLAND, OREGON	6.5	0.6	77	86	25.9	13.2	45	83
DENVER, COLORADO	5.6	-9.6	44	62	31.3	14.1	36	73
WICHITA, KANSAS	5.3	-5.4	63	74	33.6	20.8	46	79
BOSTON, MASSACHUSETTS	2.7	-5.0	58	67	27.7	18.6	56	73
CHICAGO, ILLINOIS	0.2	-8.8	68	76	28.9	16.3	58	82
FAIRBANKS, ALASKA	-18.2	-29.7	67	68	22.1	8.7	50	78
HONOLULU, HAWAII	26.2	18.8	64	79	29.2	22.8	51	67

The data and the envelope shown in figure 1(d) are consistent with the summary of 10-y surface meteorological data given in reference 40 for 11 different sites in the 48 contiguous states of the USA, except for the extremely cold winter conditions noted for Caribou, Maine; Glasgow, Montana; Green Bay, Wisconsin; and Columbia, Missouri.

The point to be noted here is that the omission of the cold, dry region of allowable temperature/humidity combinations in the lower left part of figure 1(b), below the bottom $10 \text{ dB} \cdot (100 \text{ m})^{-1}$ boundary curve from the proposed criterion in figure 1(c), is compatible with conditions likely to be encountered in a real situation. Extremely cold and dry conditions might be encountered in Antarctica or on the plateau of the Greenland ice cap, but not at many airports that are current candidates for aircraft flyover noise tests. Note also that, on the average, the extremely hot and extremely humid conditions of the upper right-hand corner of figure 1(d) are just not found in the USA.

The vertical distributions or profiles of humidity and temperature must be considered along with the limiting values in a complete specification. Actual profiles are highly variable and trend lines representing average conditions are difficult to establish especially for humidity.

A fundamental measure of moisture content used by meteorologists is the mixing ratio or the dimensionless ratio of the mass of water vapor contained in a given sample of moist air to the mass of dry air with which the water vapor is associated in the sample of moist air. A vertical profile of the middle-latitude mean annual mixing ratio is given in table 3-25 in reference 27 and is shown as the solid line in figure 2(a) for heights up to 5 km above a surface at sea level elevation. The curves are plotted in the usual meteorological format with height on the ordinate and meteorological parameters on the abscissa.

For information, figure 2(a) also shows the corresponding variation of mean annual absolute humidity, in $\text{kg} \cdot \text{m}^{-3}$, and mean annual molar water vapor concentration, in percent. Absolute humidity is the ratio of the mass of water vapor in a given sample of moist air to the total volume occupied by the sample of moist air at a specified pressure and temperature. Molar

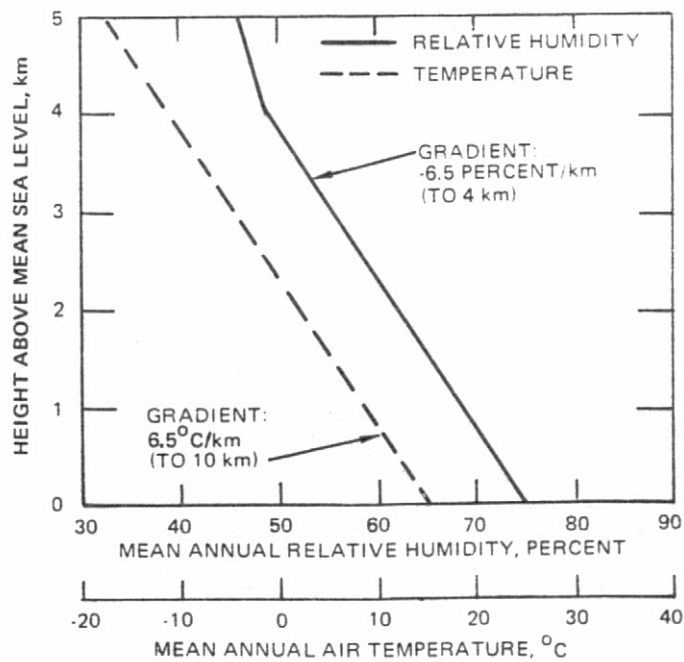
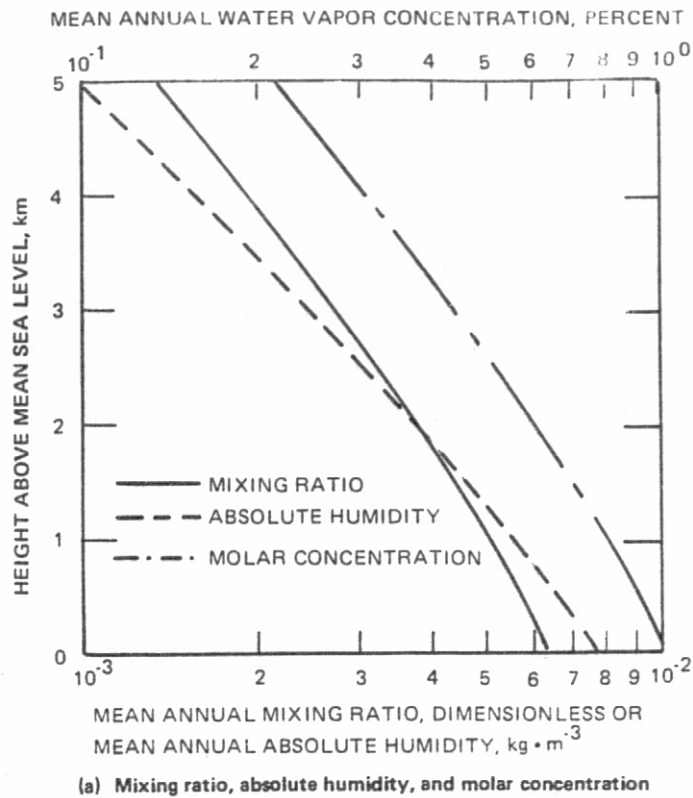


Figure 2. -Profiles of mean annual midlatitude (45° N) atmospheric humidity and temperature.

concentration (or mole fraction) for a given volume of moist air at a given temperature and pressure is the ratio of the number of moles of water vapor to the number of moles of water vapor and dry air. Absolute humidity is the basic measure of humidity used in the method of SAE ARP 866A. Molar water vapor concentration is the basic humidity measure used in the methods being developed by ANSI Working Group S1-57.

The mean annual curves shown in figure 2(a) represent the average of data with a very wide range of variability. According to reference 27, 90 percent of the actual midlatitude humidity data will range within plus or minus one order of magnitude of the mean annual line.

The mean annual variation of the midlatitude relative humidity and air temperature is shown in figure 2(b). The temperature variation is that for a U.S. Standard Atmosphere, reference 26, and represents dry air of standard composition at middle latitudes. The mean relative humidity is shown as a function of height above the surface with a gradient in the first 4 km of -6.5 percent per kilometer. The gradient of the mean temperature profile is -6.5°C per kilometer and, according to reference 26 this gradient exists to a height of 10 km.

While the gradients of the temperature and relative humidity profiles in figure 2(b) may be representative of average gradients in the atmosphere above airports where aircraft flyover noise tests might be conducted, the absolute values of temperature and relative humidity may not be appropriate. The 45-deg-north middle-latitude is actually rather north of most likely candidate test sites since it is at the latitude of cities such as Bangor, Maine; Minneapolis, Minnesota; and Salem, Oregon.

Reference 41 contains additional information on the standard variation of meteorological parameters with height to supplement the data in the 1962 standard atmosphere in reference 26. The data in table 2.1 of reference 41 describe seasonal effects on temperature and humidity at latitudes of 15°N , 30°N , 45°N , 60°N , and 75°N . Seasonal effects are described by data for the months of January and July.

The data for 30°N (defined as subtropical and representative of locations such as Jacksonville, Florida; New Orleans, Louisiana; and Houston and San Antonio, Texas) and for 45°N are shown in figure 3.

Some observations about the data in figure 3 are that, for 45°N latitude, the relative humidity decreases as the temperature increases from January to July, and, for 30°N latitude, the relative humidity remains roughly constant below 1.5 km and increases substantially above 1.5 km between January and July. We also see the expected trend that there is less seasonal variation in temperature nearer to the equator at the 30°N latitude than at the 45°N latitude.

The temperature profiles are steeper (approaching isothermal) below a breakpoint in January than in July. Above the breakpoint, the gradient is approximately the standard gradient of figure 2(b) of -6.5° C per km. The height of the breakpoint decreases between January and July.

The mean 45°N relative humidity profile of figure 2(b) is quite close to the January 45°N profile of figure 3(a).

The standard 15° C surface temperature for 45°N latitude is 4° C greater than the mean of the January and July surface temperatures. From figure 3(b), however, it does appear that a 15° C surface temperature represents a reasonable overall mean value for the continental USA. A corresponding value for surface relative humidity would seem to be about 77 percent. The 75 percent value of figure 2(b) is probably a reasonably representative number. The combination of 25° C and 70 percent relative humidity selected for reference conditions for noise-type certification do not represent commonly occurring surface conditions (and were not meant to).

Finally, we note that there are no inversions (increasing temperature or humidity with increasing height) for any of the average data in figures 3(a) or 3(b). There are kinks, and discontinuities, but no inversions.

Inversions, especially below 1 km, are relatively common in the early morning until the sun has heated the surface of the land and there has been some turbulent mixing of the atmosphere near the surface with the upper atmosphere. The morning hours after sunrise, however, are usually the most calm and may provide the best times for conducting flyover noise tests. Thus, while desirable not to, it may be necessary to conduct some flyover noise tests with temperature and humidity inversions.

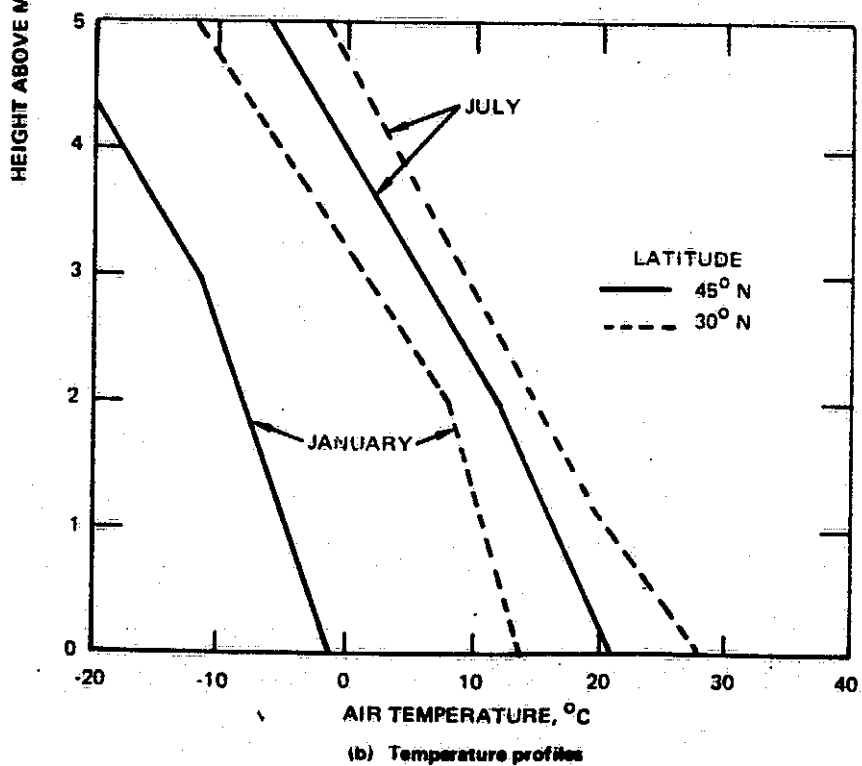
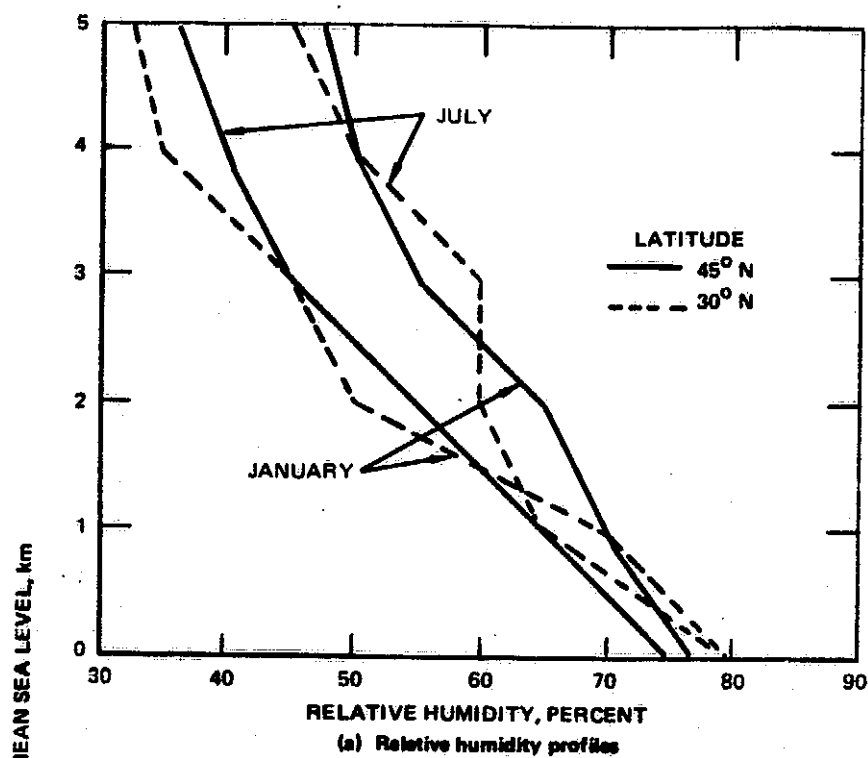


Figure 3. Seasonal effects on humidity and temperature profiles at mid- (45° N) and subtropical (30° N) latitudes.

Based on the above discussions, the following temperature and relative humidity limitations are recommended as part of the test criteria. If conditions change during a test so as to fall outside the limits, the test should be terminated and rescheduled.

- (1) Air temperature and relative humidity should be inside the allowable region described in figure 4 throughout the test and from a height above ground level of 10 m to a height at least equal to the maximum height of the test airplane occurring during the duration of any flyover noise recordings. (Note that figure 4 is the same as figure 1(c), but with the lower temperature limit extended from 2.2°C to 0°C , and with no lower limit on relative humidity except that provided by the $10 \text{ dB} \cdot (100 \text{ m})^{-1}$ boundary. This extension was considered reasonable since, without inversions, the temperature aloft will usually be colder than the 10-m surface temperature. The requirement that the conditions throughout the range of heights be within the envelope will therefore usually mean that the surface temperature will not be below 5° to 8°C . The elimination in figure 4 of the 30-percent lower limit for relative humidity in figure 1(c) was considered reasonable because of the requirement that conditions aloft along all sound propagation paths had to be within the envelope in figure 4 and because of the assumption that absorption effects occurring under nonreference meteorological conditions would be accounted for during data analysis.
- (2) Air temperature and relative humidity measurements should be made at one, or more, stationary locations, at a height of 10 m within the array of microphones, and as a function of height above-the-ground-surface by suitable airborne instruments. If the data from the stationary tower and the weather-aloft data at a height of 10 m differ by more than $\pm 0.5^{\circ}\text{C}$ in temperature or ± 1.5 percentage points in relative humidity, the reason should be determined and the differences resolved before the test proceeds.
- (3) Tests may be conducted with inversions in the temperature and relative humidity profiles, but conditions must always be within the allowable region of figure 4 throughout the range of heights and throughout the duration of all flyover noise recordings.

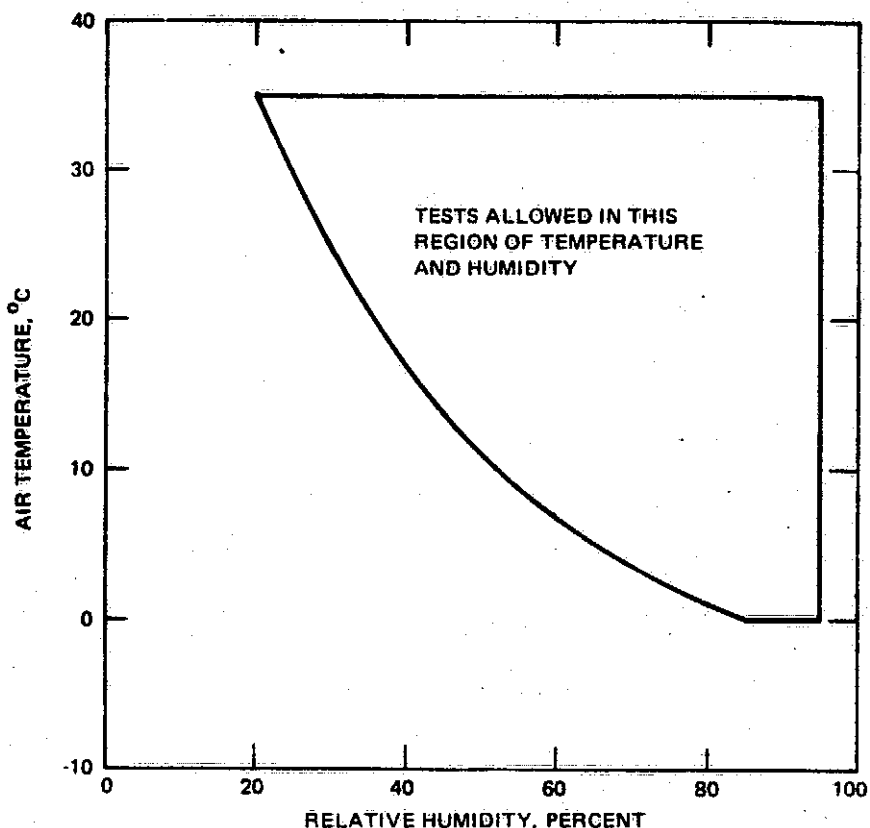


Figure 4. -Region of allowable temperatures and humidities for NASA/ANOPO flyover noise tests.

The height interval between meteorological data samples must be fine enough to resolve the extent of the inversion, preferably no more than every 20 m for strong local inversions.

- (4) The air temperature and relative humidity at the 10-m height should be as close to the reference values as possible.
- (5) The horizontal extent of the region of the atmosphere to which these restrictions are meant to apply is intended to be such that the weather-aloft data are applicable to the longest sound propagation paths at the beginning and end of each flyover noise recording, as well as the shortest sound propagation paths.

Winds. - Winds and wind gradients create special problems for outdoor noise measurements. If the receiver is upwind of the noise source, the receiver could be in a wind-created shadow zone and measure abnormally low sound pressure levels. Conversely, increased sound pressure levels could be noted at the location of a receiver downwind of a noise source. Winds also increase the level of the ambient noise.

Wind gradients and wind shears aloft may also cause the sound waves to be refracted from the path they would have followed in an atmosphere without wind gradients. Wind shear is defined here as the change in the horizontal wind occurring in a given height interval, i.e., the vertical wind shear.

Wind gradients and wind shears also affect the operation of the test airplane (and weather airplane if one is used) and may make it difficult to maintain heading, airspeed, and height. Winds not aligned with the aircraft's heading (crosswinds) may also affect the operation of the engines, perhaps causing unusual or increased noise levels or require special flying techniques that produce unusual directivity of duration patterns.

Pressure fluctuations caused by wind flowing around a microphone produce spurious noises in the recorded signal and increase the effective ambient noise level. Windscreens can reduce these spurious noises although the windscreen will affect the frequency response of the microphone (by different amounts at different angles of incidence). Furthermore, the reduction in wind noise provided by the windscreen varies with frequency and decreases (usually) as the wind speed increases.

Friction caused by the wind blowing over the surface of the land produces turbulence. The strength of the turbulence varies greatly in time and extent, both horizontally and vertically (ref. 27). Frictional effects depend on surface roughness and thermal stratification. Turbulence is also associated with wind gradients and wind shears. Inhomogeneities in wind velocity associated with 'blobs' or 'eddies' of atmospheric turbulence can reflect and scatter sound waves and result in very large (± 10 dB), short-duration amplitude fluctuations at particular locations in the sound field.

The principal atmospheric turbulence quantities of concern to sound propagation are thought to be temperature and velocity (wind) fluctuations. Temperature fluctuations cause fluctuations in the speed of sound. Velocity fluctuations can distort the path of the sound rays and hence the wavefront. The result may be scattering of the sound waves and, at a given point in the direction of propagation, fluctuations in the amplitude and phase of the sound wave. The net result may be a reduction in the sound pressure level at a microphone located in the original propagation direction because some of the originally incident sound energy has been scattered away to another direction.

Failure to recognize ray-path bends that might have occurred during propagation may mean that propagation corrections may not be applied properly and that acoustic emission angles from a source, or sources, of sound may not be properly identified.

The influences of atmospheric turbulence on sound propagation are not yet quantified (ref. 42) although one study has indicated potentially large effects (ref. 43). At the present time there does not appear to be any good method for quantitatively evaluating the effect of turbulence on sound propagation although airborne and ground-located systems are available for measuring quantities proportional to the turbulent temperature and velocity fluctuations. Until proven measurement and analysis procedures are available to account for turbulence effects, the best approach appears to be to permit tests only with calm-to-moderate steady winds and few gusts — throughout the test region and not just at the 10-m surface measurement location. (Item 5 in Appendix A describes requirements for additional research to understand the effects of atmospheric turbulence on sound propagation.)

Three of the published wind criteria for aircraft flyover noise tests (refs. 17, 18, and 25) require that the airport-reported wind speed not be greater than 10 knots and that the crosswind component be not greater than 5 knots at 10 m above the ground. Potential problems with this wording are that the airport's wind-measuring instrument may be a long distance from the microphones and therefore not capable of providing representative wind data, that the wind speed at the microphone locations may be substantially different than the airport reported wind speed, that the wind speed in the vicinity of the aircraft's flight path may be considerably different than the airport-reported wind speed, and that there is no requirement to measure winds aloft. Specification of a maximum 5-knot crosswind component at a height of 10 m is useful, but not complete. The location of the 10-m tower for the crosswind measurement is not stated and presumably is at, or near, the facility used to provide the airport-reported wind.

The proposal in reference 16 was simply that the wind speed at a height of 10 m above the ground shall not be greater than $5 \text{ m} \cdot \text{s}^{-1}$ (10 knots). Presumably, this requirement was to be met everywhere in the test area, but no specific mention was made of where the 10 m tower(s) was to be

located. Also, there was no indication whether the magnitude was that of a peak or an average value.

In addition to the constancy of the wind speed, there is the need to consider constancy of wind direction. When the wind speed is low (1 to $4 \text{ m} \cdot \text{s}^{-1}$) and there are relatively few problems with wind-induced noise on the microphone and light, or no, atmospheric turbulence, there may still be problems because the wind direction may be constantly shifting. Variability in wind direction affects the propagation of the sound waves and produces variations in the amplitude of the received sound signal. Daily changes in direction and speed caused by land and sea breezes are a related problem for certain airports.

Wind gusts can also be a major source of variability. The problems caused by gusts are similar to those caused by atmospheric turbulence. Gusts can be very high amplitude and short duration. The period between gusts will be highly variable, as will be the amplitude and duration of individual gusts. It is wise to avoid testing when the amplitude of the gusts exceeds $8 \text{ m} \cdot \text{s}^{-1}$ (15 knots).

In light of the above discussion, the following wind restrictions are recommended. If the wind speed increases above the limits during a test, the test should be terminated and rescheduled.

- (1) The steady, average wind speed should not exceed $5 \text{ m} \cdot \text{s}^{-1}$, and wind gusts should not exceed $8 \text{ m} \cdot \text{s}^{-1}$ from a height above ground level of 10 m to a height at least equal to the maximum height of the test airplane that occurs during the duration of any flyover noise recording.
- (2) The steady, average wind direction should be within $\pm 30^\circ$ of one of the runway headings and the magnitude of the cross-wind component should not exceed $3 \text{ m} \cdot \text{s}^{-1}$ over the same ranges of height and time specified above.
- (3) Measurements of wind speed and wind direction should be measured at a stationary location, at a height of 10 m within the array of microphones, and above the ground surface by suitable airborne instruments. Any discrepancies in wind speed between measurements from the 10 m stationary locations

and the weather-aloft instruments of more than $3 \text{ m} \cdot \text{s}^{-1}$ should be resolved before the test proceeds.

- (4) The horizontal extent of the region of the atmosphere to which the wind restrictions are meant to apply is intended to be such that weather-aloft data are applicable to the longest sound propagation paths at the beginning and end of each flyover noise recording, as well as the shortest sound propagation paths.

Precipitation. - Precipitation, in any form, during the flyover noise recordings is undesirable because of the noise produced, the impact on test operations, the deleterious effect on the instruments, and the inability to remove precipitation-related effects from the noise recordings in subsequent analysis.

All published test criteria prohibit testing during rain or other precipitation.

The recommended criterion for precipitation is simply that there be no measurable precipitation in any form in the region of the test site during any of the flyover noise recordings.

Pressure. - Atmospheric pressure will be a parameter of minor importance if the suggested criteria are followed. Atmospheric pressure, at a convenient height, should be measured periodically throughout the test in the vicinity of the microphones.

The atmospheric pressure will probably not be a great deal different than the standard atmospheric pressure, nor will there be much variation in pressure in the horizontal or vertical directions (for the heights involved in these tests).

The value of the pressure existing at the time of the tests should be measured, however, for use during data processing (the output of acoustic calibrators is a function of the atmospheric pressure) and data analysis (the atmospheric pressure is a parameter in determining atmospheric absorption losses and the ability of the engines to achieve sea-level takeoff-rated thrust).

RECOMMENDED INSTRUMENTATION PERFORMANCE REQUIREMENTS

Before discussing instrumentation performance, consideration must be given to the two potentially conflicting requirements for a noise-measurement program. One requirement can be described by saying that at all times the very best possible indication should be provided of the true sound pressure at a point in a sound field. The other requirement can be described by saying that a reasonable job should always be done of trying to measure the true sound pressure at any given time, but that more-important considerations are repeatability, reproducibility, and consistency.

To satisfy the first requirement, the usual approach is to start by assuming that the total data-acquisition/data-processing system should add the least possible coloration, distortion, or modification to the original waveshape of the incident free-field pressure. All relevant instrument performance requirements are assumed to be understood in detail for the best total measurement system that can achieve the objective of yielding an accurate, faithful replica of the original sound pressure signal. Instrumentation performance requirements (acoustical, electrical, mechanical, and environmental) are then written and it is assumed that anyone can put together a measurement system that will always achieve the objective so long as the performance requirements are satisfied.

There are at least two problems involved in an attempt to specify instrumentation performance requirements for a best total measurement system. First, the best total measurement system cannot be defined in any absolute sense that will be "best" not only now, but in the future. Second, if total reliance is placed on performance requirements alone, then different organizations will undoubtedly assemble measurement systems meeting the requirements, but using different instruments. Subtle differences in the design of the instruments, coupled with different test procedures, can produce differing results even though tests are conducted on the same airplane, at the same engine power setting, with the same flight path, meteorological conditions, test procedures, and data-processing or data-analyzing procedures. The differences, which may be small, will be blamed on the instruments until it is realized that additional or different performance parameters, additional details of the components of the total measurement

system, and the details of the test procedures must be specified to reduce the variability.

The magnitude of the numerical differences attributable to the use of different instruments and equipment may be small but important, especially in competitive situations or where one is attempting to demonstrate compliance with maximum noise level limits. For ANOPP purposes, it will be important, but perhaps not as critical as for a noise certification test, to consider the effects introduced by varying measurement systems all complying with the same performance requirements. Tests to validate and refine ANOPP noise-prediction procedures may be performed by various government and industry organizations. At any given time the instruments will not be all identical. Tests conducted in the future will surely use different instruments than tests conducted today.

Finally, any set of practical performance requirements (including tolerances) will be based on the characteristics of the best-performing components available for general use at the time the list of requirements is prepared.

In contrast to the listing of performance requirements to guarantee the best possible data, there is the alternative of selecting a particular system, with particular components, and writing down performance requirements consistent with the selected components. The consequence of this choice is the creation of a set of state-of-the-art performance requirements with the result that measurement systems complying with the requirements may all have the same instruments. This alternative helps assure uniformity, consistency, and intercomparability of test results. The disadvantage of the approach is that it is difficult, but not impossible, to introduce new instruments or components because of the real possibility that such changes will yield results different from the last test of the same configuration or different from a similar test conducted by another organization. For example, adoption of improved microphones having flatter frequency response characteristics over a wider range of angles of incidence, or more sensitivity with the same external dimensions, may be postponed because the test results could be different (probably by only a small amount), even though corrections for differences in frequency response and sensitivity are made as carefully as possible.

The approach that was adopted was to develop instrumentation performance requirements compatible with the best technically qualified instruments available at the time. A data-acquisition measurement system was defined based on these instruments that was also consistent with anticipated test procedures and data-processing/data-analysis methods. It was assumed that the data-acquisition system should result in the best possible measurement of sound pressures using available instruments. It was not considered necessary to be concerned about possibly inconsistent results obtained in the future using different instruments. It was also assumed that the problems of equipment obsolescence and economic burden were negligible compared to ANOPO program objectives.

A remaining consideration was whether or not to specify certain performance requirements by simple reference to published national or international documents. Because experience has shown that it is difficult to ensure clarity of meaning and unambiguous understanding of the intent of the reference, and because many (if not most) of the relevant documents were in the process of being revised, the approach adopted was to spell out the recommended performance requirements in as much detail as seemed to be required.

General Performance Requirements

All components of a field data-acquisition system should meet certain general requirements, including electrical/electronic, mechanical, design, and economic. A listing (not all inclusive) might include the following items, not in order of priority:

- operate reliably over the parameter range of interest
- be compatible with the expected range of ambient atmospheric conditions (temperature, humidity, pressure)
- over the parameter range of interest, have performance requirements compatible with the needs of the test program, including:
 - high accuracy
 - high sensitivity and low background noise in order to yield an adequate ratio of signal-to-background noise
 - adequate resolution

- wide, flat amplitude/frequency characteristic
- good linearity between output and input
- fast response time
- low starting threshold (for winds)
- no hysteresis
- repeatable measurements
- either measure by a primary technique such that no calibration is required or provide an accurate method for laboratory calibration and field checking of calibration
- have no drift in calibration or characteristics with time (good long-term stability)
- be insensitive to changes in ambient conditions or power supply
- be directly compatible (electrically and mechanically) with all other components of the total measurement system, including data processing
- have a rugged, simple design
- for stationary and balloon-borne instruments, be powered by low-voltage batteries and require only a small current drain
- be of durable construction and be made of inert materials as much as possible so as not to react to or be corroded by any of the common atmospheric pollutants such as chemicals, aerosols, and salt
- have a useful lifetime, before technical obsolescence, of at least five years
- have low weight and compact size
- be reasonable in price
- be unaffected by dust or dirt particles
- be unaffected by dew, rain, snow, or ice
- be easy to maintain
- have spare parts readily available
- for balloon-borne instruments, the instrument package should be recoverable and reusable.

All of these general requirements should be considered when assembling a data-acquisition system. The performance requirements and instruments discussed in the following sections are compatible with the general requirements outlined above.

Data-Acquisition System

The recommended data-acquisition system has six major components, as indicated schematically in figure 5. The subsystems that record the aircraft's noise level and position, and the aircraft and engine parameters, are synchronized closely in time by the time correlation subsystem. Time is also used to correlate the measurement of meteorological parameters, but the synchronization is indirect because the time rate of change of the meteorological parameters is slow compared to the time rate of change of the acoustic and aircraft parameters. At the bottom is the two-way radio communication system needed to coordinate test operations among the various field test personnel, aircraft flight crew, and air traffic control personnel at the airport.

The next sections specify the major ideal and actual performance parameters of the six subsystem components of figure 5.

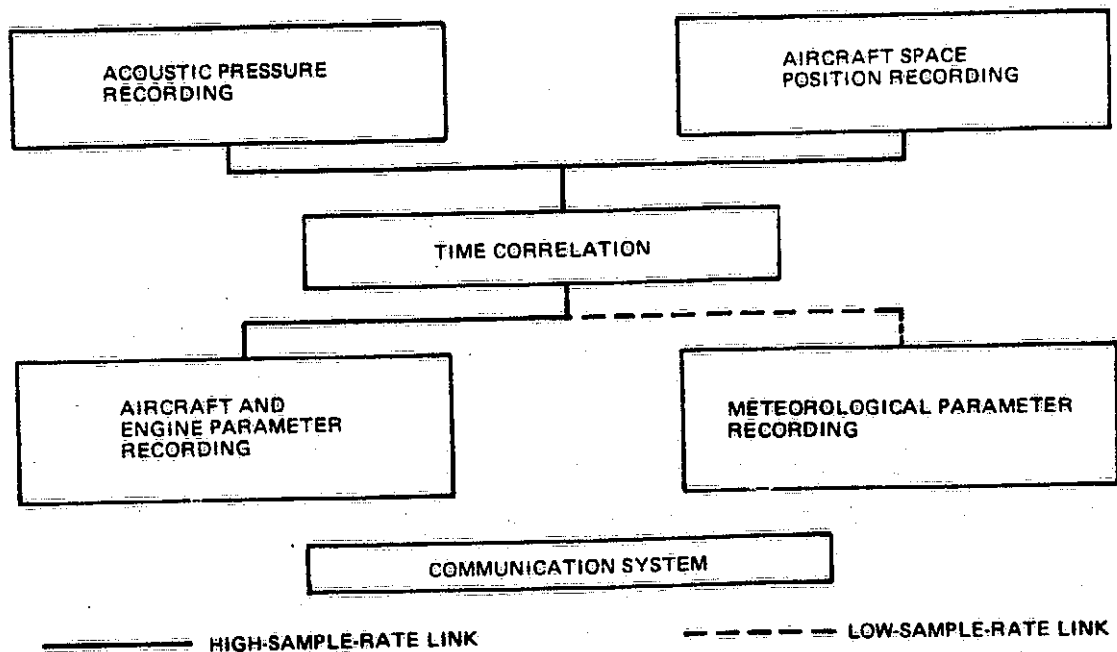


Figure 5. -System components for aircraft flyover noise data acquisition.

Acoustical

The recommended test plan includes provisions for several acoustical data-recording channels at fixed locations under and to the side of the aircraft's flight path. Although it is possible to use a single-channel (or two-channel) battery-powered direct-recording magnetic tape recorder (along with a qualified operator) at each noise measurement location, experience has shown that, for controlled engineering research testing, more consistent, more accurate, and more reliable results can be obtained using a centrally located multiple-channel magnetic tape recorder rather than several separate single-channel recorders. Multiple-channel tape recorders typically have 14 channels of information recorded on 25.4-mm (1 inch)-wide magnetic recording tape.

The recommended system components for recording of acoustical data are shown in figure 6. The microphone system for each data-recording channel extends from the windscreen to the input to the recording system. Data recording in the field is done on a multiple-channel magnetic tape recorder.

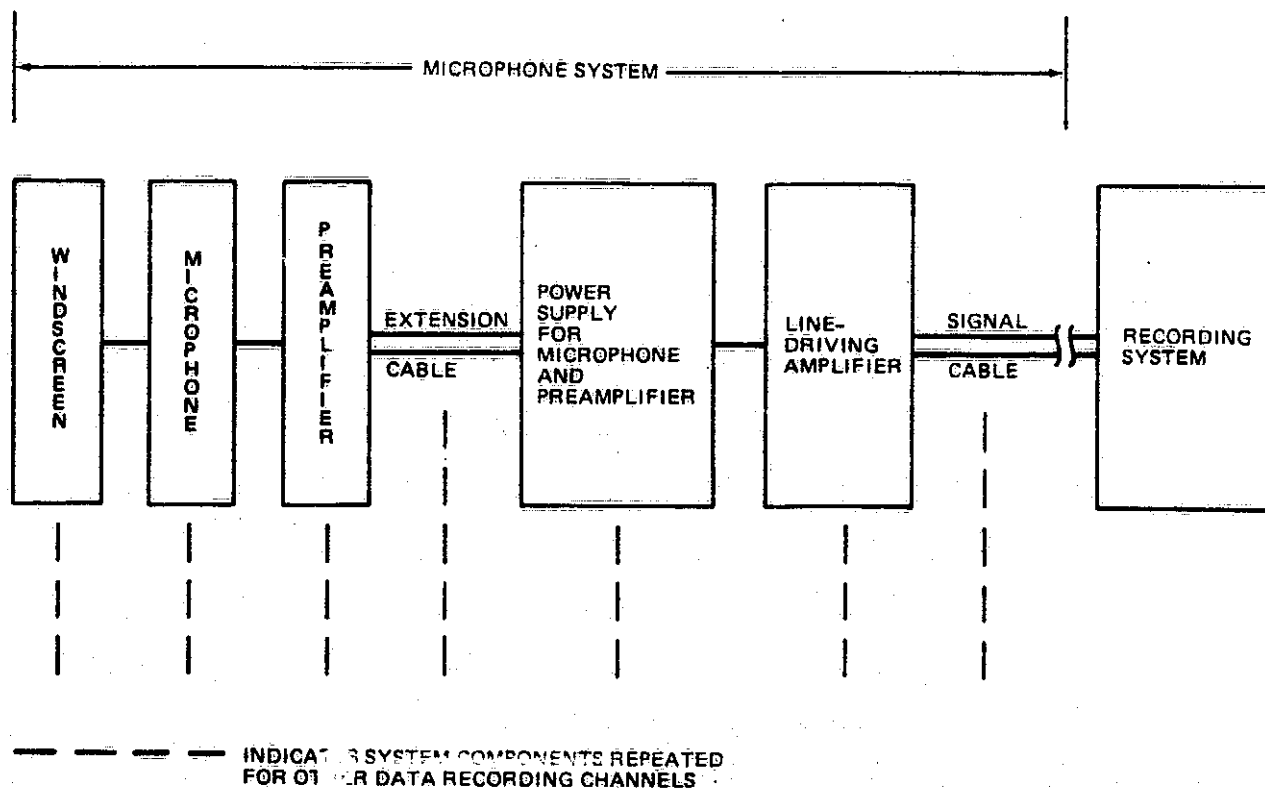


Figure 6. -Components of microphone and data-recording systems.

Microphone system. - The microphone system shown in figure 6 is based on the use of high-quality air-dielectric capacitor microphones and associated preamplifiers. This choice was based on the following considerations:

- relatively flat frequency response
- wide dynamic range
- good sensitivity
- small variation in sensitivity with angle of incidence
- low internal background noise
- good long-term stability
- relatively insensitive to environmental factors
- availability of documented electroacoustical characteristics
- availability of calibration equipment
- good reliability

Ideally, a microphone system should have flat amplitude/frequency response extending well below and well above the nominal frequency range of interest. This flat frequency response should be independent of angle of incidence from 0° to 180° (true omnidirectionality). The internal background electrical noise should be so low, and the amplitude of the sound pressure when the waveshape starts to become distorted should be so high, that the dynamic range easily encompasses the full range of signal amplitudes to be recorded. The performance of the microphone should be independent of environmental factors such as humidity, temperature, pressure, vibration, magnetic fields, and solar radiation. The microphone's characteristics should be determined at the factory at time of manufacture and should not change with time. The sensitivity of the microphone should be high and the output impedance low so that there is no problem driving long signal transmission cables; the signal level at the tape recorder should always be adequate. The dimensions of the microphone should be small enough that the microphone causes only negligible disturbance of the sound field. Appropriate calibration equipment should be available for easily checking the microphone's performance in the field and for accurate calibrations in a laboratory. The reliability of all components of the system should be high because of basic design and several years of manufacturing experience. Replacement parts, if needed, should be readily available.

The 12.7-mm-diameter air-capacitor microphone, and associated pre-amplifier, seemed to be the most reasonable choice for satisfying the set of ideal requirements. Calibration accessories and replacement microphones are readily available. The dimensions are small enough that high-frequency interference and diffraction effects occur mainly above 10 kHz. The output impedance of the preamplifier is low. A line-driving amplifier is needed, however, as indicated in figure 6, to handle the wide range of signal amplitudes and the resistive and capacitive loading of long runs of cable between the power supply and the tape recorder. When exposed to moderate temperatures (20° to 25°C) the microphone design is very stable, with a measured change in sensitivity (due to aging) equivalent to 1 dB in no less than 300 years.

Except for humidity and wind, the recommended microphone system should be relatively unaffected by environmental factors likely to be encountered in testing of aircraft flyover noise. There should be no influence of temperature on the operation of the microphone and preamplifier in the range from -10° to +40°C, which is more than the range of temperatures allowed in figure 4. The effects of normal variations in atmospheric pressure are negligible. Vibration, magnetic fields, and solar radiation effects also are negligible, including vibration induced by the aircraft noise signal itself.

Since, by figure 4, tests are permitted in quite humid atmospheres, there is a potential problem with humidity. If condensation occurs in the air between the two charged plates of the capacitor (i. e., between the diaphragm and the backing plate), then electrical arcs will strike between the plates. The intermittent arcing usually does not cause physical damage but does generate equivalent short-duration popping or frying noises in the recordings. To avoid humidity problems, the preamplifier should contain a built-in heating device to keep the microphone warm. Condensation will not occur if the temperature inside the microphone is kept above the local dew-point temperature. If the heating device is not adequate to prevent condensation, a dessicant system is available to supplement the heater.

To minimize wind-induced noise (occurring at wind speeds below the recommended limit) the microphone should be enclosed by a windscreen at all times during a test.

The recommended windscreen is one made from open-cell uncompressed polyurethane foam. A spherical shape is preferred with a small hole

for insertion of the microphone. The diameter of the windscreen should be at least 0.09 m; larger windscreens will provide more reduction of wind noise. The reduction of the wideband wind-induced noise level should be at least 10 dB for a steady wind speed of $10 \text{ m}\cdot\text{s}^{-1}$. The effect of the wind-screen on the free-field sensitivity of the microphone (in the absence of wind) should not exceed $\pm 1.0 \text{ dB}$, relative to the sensitivity at 250 Hz, over the range of frequencies from 45 to 11 200 Hz for any angle of incidence from 0 to 180° .

The output impedance of the preamplifier should be low enough so that the preamplifier and the power supply can be separated by as much as 12 m of cable with negligible impact on frequency response for frequencies between 45 and 11 200 Hz.

For a given stiffness and mass of the diaphragm, the frequency response of a microphone and preamplifier combination is a function of the amount of internal damping and the angle at which an incident sound wave impinges on the diaphragm. As described below under Recommended Data-Acquisition Procedures, microphones will be oriented so that the noise from the aircraft impinges on the microphones at approximately grazing incidence at all times throughout the recordings. The recommended frequency-response characteristics, therefore, are primarily directed at ensuring reasonably flat response for grazing incidence. Grazing incidence means in the plane of the diaphragm or 90° from the axis of the microphone normal to the plane of the diaphragm.

The recommended requirements for the free-field frequency response of the combination of microphone and microphone preamplifier (no windscreen) are as follows:

- (1) The variation in sensitivity in the plane of the diaphragm (i. e., for grazing incidence) should not exceed $\pm 0.5 \text{ dB}$, relative to the sensitivity at 250 Hz, over the frequency range from 45 to 11 200 Hz
- (2) The variation in sensitivity should not exceed $\pm 2 \text{ dB}$, relative to the sensitivity at 250 Hz, within the angles of 60° to 120° from the axis normal to the diaphragm ($\pm 30^\circ$ about grazing incidence) over the frequency range from 45 to 11 200 Hz.

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Sensitivity here is defined as the ratio of the root-mean-square (rms) voltage at the output of the power supply to the rms acoustic pressure that would exist at the position of the diaphragm in the absence of the microphone (i. e., the free-field acoustic pressure).

The dynamic range of the combination of the microphone and microphone preamplifier should be at least 100 dB. Dynamic range is defined here as the difference between the level of high-amplitude sound pressure causing a total harmonic distortion of 3 percent and the level of the wideband electrical background noise. Total harmonic distortion of the signal at the output of the power supply, for a pure sinusoidal acoustic signal of any frequency between 45 and 11 200 Hz at the input to the microphone, is the ratio, in percent, of the rms amplitude of all the harmonics of the fundamental signal frequency to the rms amplitude of the fundamental signal frequency.

The electrical background noise is determined with the microphone replaced by an equivalent electrical impedance. The voltage (or equivalent background noise level) is measured at the output of the power supply with a wideband voltmeter (a bandwidth of 20 Hz to 200 kHz is recommended). The wideband or linear background noise level should not exceed 35 dB, re 20 μ Pa. The corresponding A-weighted electrical background noise level should not exceed 20 dB. An approximate check of the high-frequency (above about 1000 Hz) electrical background noise can be obtained by placing an acoustical calibrator over the microphone with the calibrator turned off. For many tests it is only high-frequency background noise that causes interference problems and this method of shielding the microphone may be adequate to evaluate the effect of high-frequency background noise. However, it is more accurate and provides data on the complete spectrum of electrical background noise to replace the microphone by an equivalent electrical impedance and, therefore, the use of a dummy microphone is recommended.

The power supply should be battery operated and should supply all the voltages needed to operate the microphone and microphone preamplifier, including the direct-current (dc) polarizing voltages for the microphone and the dc voltage needed for the heating element in the preamplifier. The power supply should be designed so that the batteries can provide the necessary electrical power for at least 10 h of continuous operation at any temperature

in the range from -10° to $+40^{\circ}\text{C}$. Since the sensitivity of the microphone depends on the value of the polarizing voltage, the polarizing voltage must remain practically constant. The maximum allowable drift in the value of the nominal polarizing voltage is ± 1.0 percent in a 10-h period of constant operation in temperatures ranging from -10° to $+40^{\circ}\text{C}$ and for any battery voltage likely to be encountered in the same period as a result of normal battery drain. The output impedance of the power supply should not exceed 100 ohms.

If there is a choice in polarization voltage, choose the nominal polarizing voltage that gives the greatest sensitivity with least electrical background noise. This choice will be correct for most flyover noise tests unless the expected maximum sound pressure levels are so high (say more than 130 dB) that the output voltage from the microphone exceeds the maximum rated output voltage (i.e., the output voltage is above the distortion limit). If there is danger of clipping the output signal (introducing large amounts of distortion), then choose a lower polarization voltage to reduce the sensitivity of the microphone (or use a less sensitive microphone with the higher polarization voltage) and keep the output voltage below the maximum rated value. The use of a less sensitive microphone with the higher polarizing voltage should not mean that there is any degradation in the microphone's frequency response.

Signal cables between the power supply and the central magnetic tape recorder could be as long as 3000 m. The power supply is essentially a unity gain device; therefore, the signal current available from the microphone preamplifier, and hence the signal current at the output of the power supply, is not likely to be enough to drive 3000 m of cable without an intolerable reduction in amplitude. The reduction is due to resistive losses in the cable and substantial rolloff of the high-frequency content of the signal due to capacitive loading. The line-driving amplifier shown after the power supply in figure 6 is required primarily to increase the signal current at the input to the long extension cables. The line-driving amplifier should be a battery-powered operational amplifier with very high input impedance, and a maximum rms output current capacity on the order of 20 milliamps (mA). Such amplifiers are commercially available.

Because neither the microphone power supply nor the line-driving amplifier may be qualified for long-duration outdoor applications, it is

recommended that they both be enclosed in a vented container to provide protection from environmental effects and vandals. Environmental factors include rain, dust and dirt, insects, and small and large animals. The container should also offer reasonable protection from malicious vandalism and theft.

The cable between the line-driving amplifier and the tape recorder should have the following characteristics:

- low resistance and low capacitance per unit length to minimize signal losses;
- tough insulation to discourage rodents from chewing on, or through, the cable and to allow a vehicle to drive over the cable several times without abrading the insulation;
- high tensile strength so that the cable can be stretched out and pulled without breaking, yet not so stiff that it cannot be readily recoiled;
- low cost per unit length; and
- low salvage value so that it can be considered expendable if necessary and so that theft of the cable will be discouraged.

It is not necessary to use electrically shielded cable. Cable consisting of an unshielded twisted pair of insulated wires is adequate. A core of pure copper wires should be avoided because the high initial cost and high salvage value encourage theft. Steel-jacketed copper wire known as "battlefield telephone cable" has been used with good success. Pickup of radio-frequency interference by the cable from nearby radio broadcasting towers, air-traffic control signals, and transmissions from the test aircraft can be avoided by terminating one end of each cable (say the tape-recorder end) in a transformer. The transformer isolates the cable from an electrical ground and provides desirable voltage gain.

The support or stand used to hold the microphone and preamplifier at the desired location above the ground surface deserves some discussion. The dimensions of the support (or the elements of the support) within 1 m of the microphone should not be larger than 2 cm to prevent acoustical reflection and diffraction effects in the frequency range of interest. The orientation of microphone diaphragm with respect to the aircraft's flight path should be

capable of being adjusted and set to specified angles through a range of at least 90° with an accuracy of $\pm 2^\circ$.

To be able to achieve the desired height above the ground surface and yet retain a reasonable degree of access to the microphone, there are basically two choices for supporting the microphone: a telescoping tower or a hinged tower. Either of these towers could be transported on a trailer or pickup truck. With the crank-up telescoping tower, the microphone cable could run down inside the tower and be attached to the structure of the tower at short regular intervals with an easy, but secure, fastener such as a strip of velcro tape. The hinged tower would be hinged at the base and the microphone cable would be inside to prevent the cable slapping against the tower.

Both tower designs may require guy wires or stays to ensure stability and vertical orientation. The guy wires could be attached to screw-type soil anchors. The soil anchors would be installed, prior to starting the tests, at preselected and surveyed locations for the microphones. The need for guy wires and soil anchors is not obvious, however, since the tests are only conducted during periods of low to calm winds. Thus, both tower designs could be free-standing towers with three outriggers near the base.

The telescoping towers, while more compact, would be more time consuming to erect and would require a separate trailer (and probably a separate vehicle) for each tower.

The hinged or pivoted tower design would have an advantage in that it should be easier and less time consuming to erect and take down. The tower could be an untapered, hollow, aluminum-alloy extrusion of the type used for a sailboat mast or spar. A suitable design would have a round or oval cross-section with a mass per unit length of no more than $4 \text{ kg} \cdot \text{m}^{-1}$ and a wall thickness of no more than 4 mm. Since the stiffness and area moment of inertia of such a design are quite high and since the mass of the microphone, pre-amplifier, and cable are quite small, one set of guy wires or outriggers should be sufficient. Presumably, the microphones would be taken down if there was any danger of exposure to high winds or storms.

The design of a hinged microphone tower should be such that one person could raise or lower the tower. Figure 7 shows a conceptual design for a

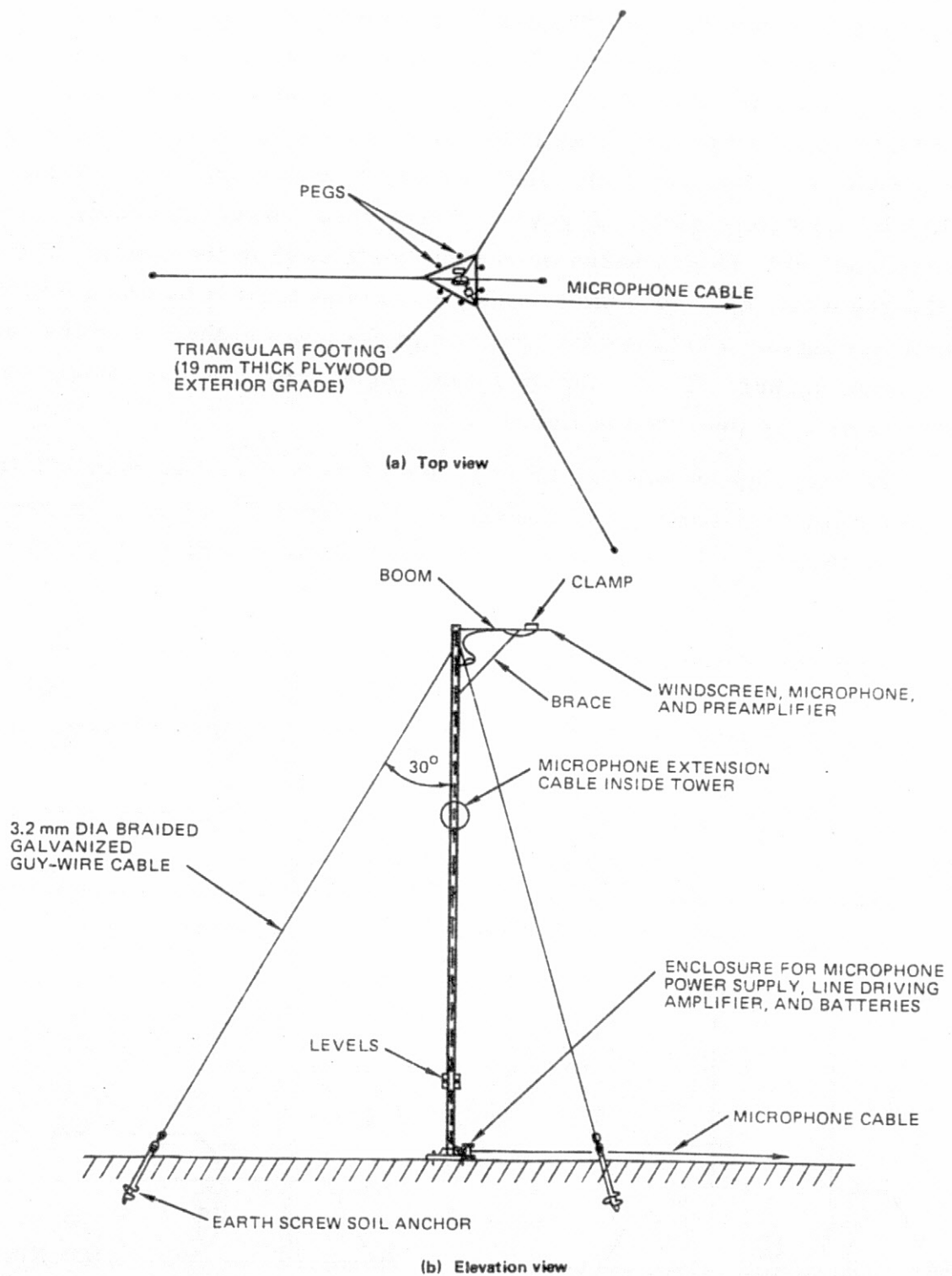


Figure 7. -Microphone tower.

hinged microphone tower. The tower is pinned to a sole plate, such as the one shown in figure 8, made from welded aluminum plate. The bolt through the sole plate and the base of the tower moves down or up in the slot when the tower is raised or lowered. The sole plate is bolted to the triangular plywood footing to support the tower, as indicated in figure 7. All the towers needed for a multiple-microphone installation could be transported on a single trailer pulled by a single vehicle. If guy wires are used, towers probably would be transported with the guy wires permanently attached to the tower. The length of the guy would be adjustable to allow for nonflat terrain by using a block and tackle arrangement between the free end of the guy and the eye of the earth-screw soil anchor. The minimum guying angle where the guy attaches to the tower is 30° , as indicated in figure 7.

The microphone booms, braces, and clamps should be removed from the tower for transporting and should be attached to the tower after removal from the trailer. The microphone extension cable is fixed to the inside of

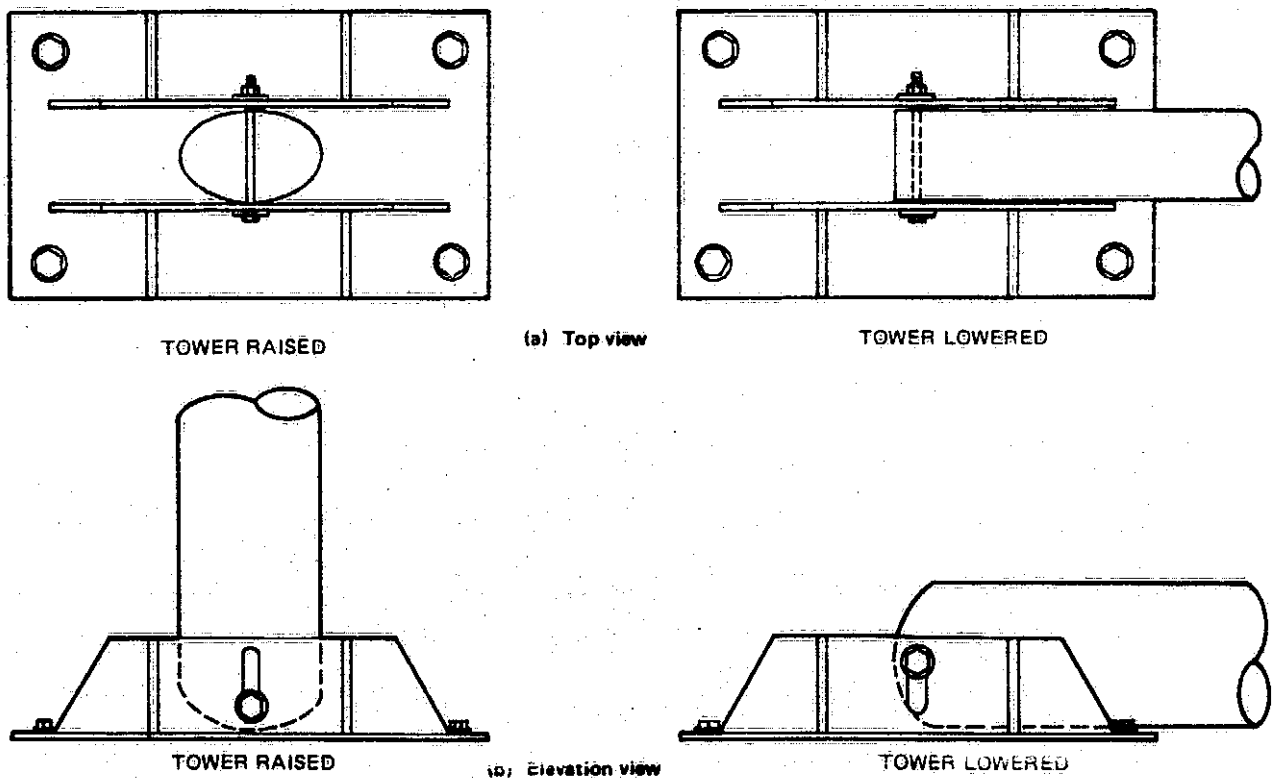


Figure 8. -Sole plate for microphone tower.

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the hollow pole with a short length of cable and the female cable connector projecting from a grommetted hole near the top of the tower; a longer length of cable and the male connector project from a grommetted hole near the base of the pole for attachment to the power supply inside the enclosure strapped to the plywood footing board.

Protection from lightning strikes, if required, could be provided by attaching a grounding strap to a metal rod driven into the earth near the base of the tower.

Hinged microphone towers, 10 m tall, similar to those described above, have been used around an engine test stand in Southern California for a number of years with good results.

Recording system. - The data-recording system has fewer components and, as shown in figure 9, consists essentially of a single multiple-channel tape recorder with appropriate termination and signal-conditioning equipment for each acoustical data channel. Signal-monitoring equipment should also be available for checking system performance, determining the duration of the flyover noise recordings, and monitoring ambient noise levels.

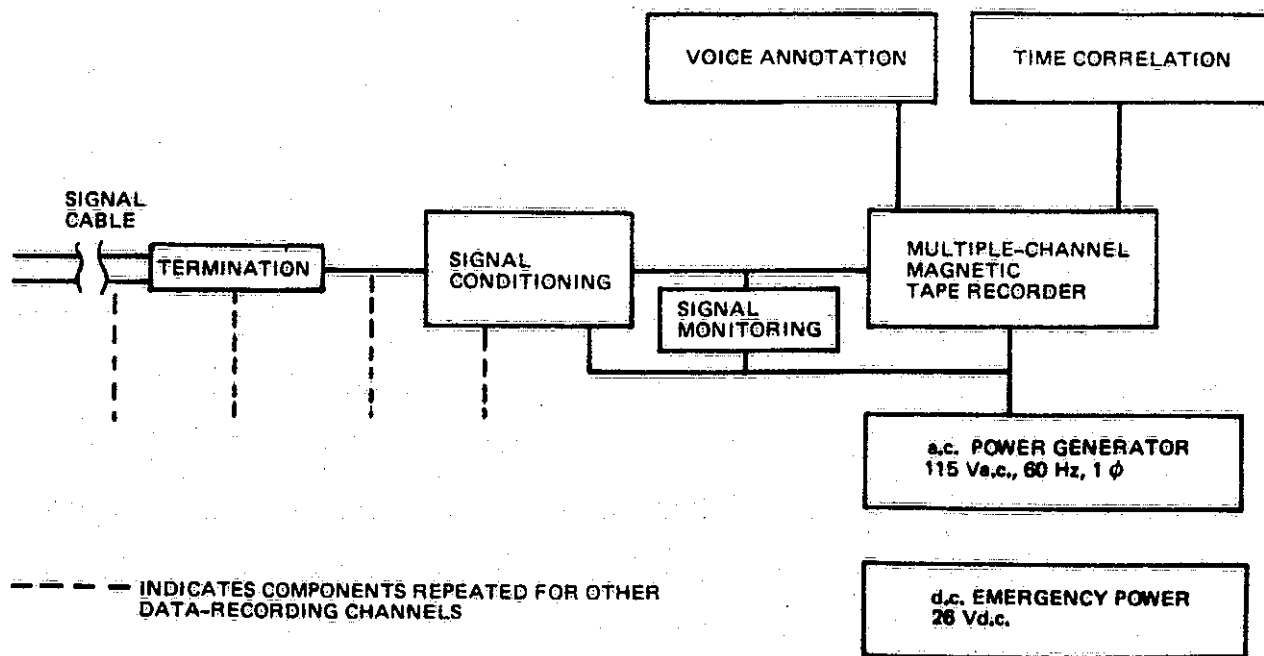


Figure 9. — Components of data-recording system

The characteristics of the data-recording system should not be considered only by themselves. Performance requirements for the data-acquisition tape recorder should be compatible with, and be developed with, processing system. For the purpose of this report, it was assumed that the electromechanical performance of the components of the data-processing system would be equal to, or better than, the performance of the components of the data-acquisition recording system.

All of the available documentation on requirements for flyover noise measurements (refs. 16, 17, 18, 20, and 25) contain some performance requirements for a data-acquisition recording system. The requirements, however, are mainly applicable to direct-record systems; none of the published requirements is concerned solely with a system based on modern multiple-channel FM tape recorders, except for the magnitude of (1) the amount by which the standard recording level should be below the maximum recording level, and (2) the amount that the electrical background noise level should be below the maximum record level. The following discussion considers some of the differences between direct and FM recording.

The test procedure recommended in this report requires a single 14-channel tape recorder. The acoustic pressure signals are transmitted to the central recorder by signal cables. Multiple-channel tape recorders of instrumentation quality, and with direct-record electronics, are not acceptable for recording the acoustic pressure signals because the signal-to-noise ratio, low-frequency response, and amplitude/frequency response curve are all not as good as with FM electronics. Some one- or two-channel direct-record tape recorders have characteristics comparable to those of modern 14-channel FM tape recorders in the audible range of frequencies, but these smaller recorders are not relevant to the recommended test procedure.

With multiple-channel instrumentation-grade direct recorders, the low end of the nominal frequency response curve will be down 3 dB at a frequency of approximately 200 Hz. This limitation makes it unfeasible to obtain acoustical data to 45 Hz. The amplitude/frequency response of direct recorders is typically only within ± 3 dB of a flat response at frequencies above 200 Hz.

With FM recording, frequency response at various levels of input voltage does not vary significantly. Amplitude stability variations caused by variations in the quality of the oxide coating on different reels of tape are not important because FM recording is amplitude-saturation recording and only frequency deviations are detected.

With FM recording, amplitude variations are recorded as deviations (modulations) of the frequency of a fixed high-frequency carrier signal. The maximum frequency deviations are set by the tape-recorder manufacturer, with ± 40 percent a typical value according to standards established by the Inter-Range Instrumentation Group, or IRIG (ref. 44). The maximum voltage of an input signal in the nominal frequency range of the tape recorder is set to correspond to ± 40 percent frequency deviation. Because the recording process involves frequency variations rather than amplitude variations, amplitude distortion introduced by the record and reproduce tape recorders can be quite small with the amplitude of the third harmonic of a sinusoidal signal typically being no more than 1 percent of the amplitude of the fundamental frequency of the wave.

With FM recording, four characteristics are uppermost in importance for specifying performance. These characteristics are: (1) signal-to-noise (S/N) ratio, (2) frequency response, (3) speed stability, and (4) amplitude linearity.

The S/N ratio is a function of tape speed, carrier frequency, and upper amplitude-response cutoff frequency. Because of the large number of variables, standards for FM tape recording were set several years ago by the IRIG organization. IRIG is principally concerned with the problem of recording telemetered data. Various recording bands, and groups within bands, have been established for various combinations of tape speed, cutoff frequency, and carrier frequency. The IRIG standards also cover various electrical and mechanical characteristics of tape recorders as well as magnetic recording tape to ensure that a recording made on one manufacturer's tape recorder can be played back on another manufacturer's recorder without degradation in performance (or even for the same type of recorder but with recordings made by one organization and data processing by another).

For a given carrier frequency and a given cutoff frequency, the S/N ratio can be increased by increasing tape speed as shown by the following typical values:

Carrier Frequency, kHz	Cutoff Frequency, kHz	Tape Speed, in. s ⁻¹	IRIG Band	S/N Ratio, dB
54	10	15	Wide, Group I	48
54	10	30	Intermediate	50
54	10	60	Low	52

The gain in S/N ratio in going from 30 to 60 in. s⁻¹ in tape speed probably would not be considered sufficient to justify the increase in tape consumption. IRIG low bands are rarely used by modern data-recording systems. Most systems use either IRIG intermediate band or wideband, group I. A wideband group II is available with much higher cutoff frequencies for the same tape speed, but with an S/N ratio approximately 15 dB lower.

For a given IRIG band and given S/N ratio, the cutoff frequency can be increased by proportionally increasing tape speed and carrier frequency as shown below for IRIG intermediate band.

Carrier Frequency, kHz	Tape Speed, in. s ⁻¹	Cutoff Frequency, kHz
13.5	7.5	2.5
27	15	5
54	30	10
108	60	20
216	120	40

Tape speeds of 60 and 120 in. s⁻¹ would only be considered for recordings of short duration. The maximum practical tape speed for recording several minutes of data on large reels of tape (typically 14-inch (35.56-cm) diameter) is 30 in. s⁻¹. (A 14-inch-diameter reel contains approximately 9200 ft of tape and provides about an hour of data recording time at a tape speed of 30 in. s⁻¹.) With this choice of tape speed, the S/N ratio accompanying IRIG intermediate-band electronics is a reasonable compromise, assuming the 10-kHz cutoff frequency is adequate. The corresponding carrier frequency then will be 54 kHz.

As noted above, within the constraints of the IRIG standards, the upper cutoff frequency can only have certain specific values. The lower cutoff frequency is not an item of concern because frequency response with FM extends to dc or zero hertz. Within the nominal frequency range, the recorder can have either nominally flat amplitude/frequency response or nominally linear phase/frequency response. For flyover noise recordings, the usual practice is to choose flat amplitude/frequency response and not worry about phase information. A typical frequency response requirement for IRIG intermediate band with 30 in. s^{-1} tape speed, 54 kHz carrier frequency, and 10 kHz cutoff frequency is for the response on playback to be within $\pm 0.5 \text{ dB}$ of the response at 100 Hz, throughout the range from dc to 10 kHz. Above 10 kHz the frequency response, per IRIG standards, is rolled off with a low-pass filter having an ultimate slope of -18 dB/octave .

In the above discussion, S/N ratio is used as the ratio of the rms voltage of a wideband signal (say, a nominal white random-noise signal) at the output of a recorder to the rms voltage at the output of the same recorder on playback with no input signal. A typical input voltage for ± 40 percent deviation is 1 Volt rms (1000 mV). Assuming the reproduce amplifier is set up to give 1 Volt output for 1 Volt at the input to the record amplifier, the output voltage will be 1000 mV rms for a 1000-mV rms input signal. A typical S/N ratio, for the selected recording conditions, might be 50 dB, meaning that the wideband electrical background noise voltage is 3.2 mV [$50 \text{ dB} \approx 20 \log_{10} (1000/3.2)$] at the output with the input signal to the record amplifier shorted to ground. We note here that a wideband electrical background noise of 3.2 mV rms is about two orders of magnitude more than the wideband electrical background noise from the recommended microphone system. Note also that the 50-dB ratio is defined in terms of wideband rms voltages (a bandwidth, say, from 2 to 200 000 Hz) and that larger S/N ratios will be obtained for narrower ranges of frequency such as 1/3-octave bands. Determination of S/N ratio as a function of frequency is recommended for the complete data-recording/data-processing system. (Item 8 in Appendix A reviews requirements for larger S/N ratios than are currently available for 14-channel FM tape recorders.)

With respect to speed stability, since flutter and hence S/N ratio are a function of the constancy of the tape speed, it is necessary that the tape transport mechanism be designed to maintain precise tape speed throughout the length of a reel of tape. Moreover, the tape speed of the data-acquisition recorder must be the same as that for the data-processing recorder to avoid frequency shifts in the test results. By comparing the signal from a photo-tachometer counting pulses of light reflected from a lined disc mounted on the capstan motor to a frequency generated by a temperature-compensated crystal, tape speed on a given recorder can be constant within ± 0.1 percent of the nominal tape speed. Thus, tape speed on playback could be 0.2 percent different than the tape speed during recording.

However, since it is likely that the tape recording could be played back on a different tape recorder than the one used in the field for recording, it is recommended that, instead of a capstan servo-control system, a reference frequency of either 50 or 100 kHz (meeting IRIG standards at a tape speed of $30 \text{ in} \cdot \text{s}^{-1}$) be recorded on one of the data tracks, preferably a track near the center of the tape. The reproduce recorder will then use the reference frequency signal in a servo-controlled system to make the reproduce tape speed follow the record tape speed. With the reference frequency arrangement, the overall long-term stability of tape speed should not exceed ± 0.005 percent of the nominal tape speed.

The amplitude of the output voltage from the reproduce recorder should be a linear function of the amplitude of the input voltage. Typically, the peak-to-peak deviation should be less than ± 0.5 percent of a best straight line fit between output voltage and input voltage, over the range of output and input voltage for a given tape recorder or a given data system.

The above discussion has described four characteristics of FM tape recorders: S/N ratio, frequency response, tape speed stability, and amplitude linearity. The one remaining item that needs to be discussed is the standard record level. Standard record level is that value of wideband rms voltage at the input to the recorder above which it is not prudent to attempt to record data, except rarely and only by small amounts.

According to IRIG standards, the maximum recording level for FM recorders is that voltage that gives ± 40 percent frequency deviations and no

more than 1 percent third-harmonic distortion for frequencies up to 0.1 times the nominal upper cutoff frequency. Common practice is to set up a tape recorder to achieve the ± 40 percent frequency deviation for a 1000 mV rms sinusoidal signal, or, for convenience, a 1414 mV dc signal. The dc signal voltage is equivalent to the zero-to-peak voltage of a sinusoidal wave. Both + and - 1414 mV dc signals are used to check the + and - values of frequency deviation, with positive going voltages corresponding to increasing frequency.

Since most aircraft sounds are rather random in amplitude, the standard record level should be set about 10 dB below the maximum sinusoidal record level to prevent clipping and distortion of occasional random high-amplitude peak signals, i. e., signals with high crest factors. Thus, if the maximum record level is 1000 mV rms for sine waves, the standard record level is about 316 mV rms for random noise [$10 \text{ dB} = 20 \log_{10} (1000/316)$]. One function of the signal-conditioning equipment shown in figure 9 is to allow the tape-recorder input voltage to be kept in the range between 250 to 350 mV rms. This statement is not meant to imply that any adjustment of gain or attenuator setting is allowed while recording.

The level of the input signal that is referred to above as the standard record level is that of the maximum value of wideband rms noise occurring during the duration of a flyover for any microphone channel. This maximum signal level must be predicted in advance either on the basis of previous experience or by flying a practice run to determine nominal gain/attenuator settings for all data channels. Since gain cannot be adjusted during a recording, the signal level at times before and after the time of the maximum signal will be much less than at the time of the maximum. For some flight conditions on some aircraft, the value of the signal at off-peak times could be 30 to 40 dB below the value of the maximum signal (assuming the wideband level of the ambient noise was low enough to allow the low levels to be measured). Thus, if the maximum wideband rms input signal was 316 mV, then signal levels of 3 to 10 mV rms could appear at the input to the tape recorder. It may not be possible to recover wideband signals as low as 3 to 10 mV rms because of the limited S/N ratio of currently available commercial FM tape recorders. This observation emphasizes the requirement to estimate as closely as

possible the maximum value of the input signal at each microphone for each run in order to provide as much dynamic range as possible by recording the maximum aircraft noise signal at a rms voltage near the standard record level.

Referring again to figure 9, the termination equipment indicated at the end of each long signal-transmission cable should include special items needed to minimize losses in the strength or frequency content of the signal. No unique performance specification is required, but consideration might be given to the use of a step-up transformer to isolate the cable from electrical ground (reducing radio-frequency pickup) and to provide some voltage gain. A resistive-pad network might also be included to ensure a low electrical impedance for cable termination (say, 100 ohms or less) to prevent excessive high-frequency rolloff in conjunction with the capacitance of the cable. Other special features could be included that are specific for the particular data-recording system.

Finally, we note that neither the above discussion nor figure 9 has mentioned the use of pre-emphasis networks. Pre-emphasis networks are sometimes used as part of the signal-conditioning equipment to provide an electrical boost to the high-frequency content of the input signal. The use of pre-emphasis is specifically not recommended.

Many organizations involved in aircraft flyover noise testing do use some kind of pre-emphasis network. Pre-emphasis is justified because of the serious reduction in high-frequency signal strength that occurs after propagation through the atmosphere. If, as is the case for many aircraft noise signals at engine power settings near to takeoff power, the spectrum of the signal is controlled by low frequencies, then the available S/N ratio may put the high-frequency part of the signal below the background electrical noise level. The loss in high-frequency signal may, or may not, be a problem depending on the requirements for data analysis and reporting. Pre-emphasis boost can also introduce spurious high-amplitude signals of very high frequency unless the pre-emphasis is rolled off above, say, 15 kHz, or a low-pass filter is included to protect the tape recorder. Pre-emphasis aggravates any problem with high-frequency ripple that may be riding on the

nominally sinusoidal low-frequency signal used to check system sensitivity and to provide a reference signal level.

It is also necessary to ensure that the exact converse of pre-emphasis is provided for each data channel during data processing. Finally, there is the question of recording high-frequency tones with a pre-emphasis network in the circuit. Tones in the 3150, 4000, 5000, 6300, 8000, and 10 000-Hz $1/3$ -octave bands from various turbomachinery stages could be over-emphasized (especially if near a band-edge frequency) with subsequent problems for data processing.

When the aircraft noise signals are above the electrical background noise of the data-acquisition system, pre-emphasis networks are not considered to be required because it is anticipated that an accurate analytical techniques will be available to account for atmospheric absorption effects and to provide reliable adjustments between test and reference conditions. Pre-emphasis should be considered when the high-frequency components of the aircraft noise signal are expected to be less than the level of the electrical background noise.

In summary, the recommended performance requirements for each channel of the multiple-channel FM magnetic tape recorders in the data-recording/data-processing system are:

- (1) The signal-to-noise ratio should be at least 50 dB below maximum record level. (The signal-to-noise ratio is defined as 20 times the logarithm [base 10] of the ratio of the rms voltage of a wideband random noise at the input to the tape recorder, when operating at the maximum design frequency deviation, to the wideband rms voltage at the output of the same tape recorder [operating as a reproduce recorder] when the input to the data-acquisition recorder is shorted. The maximum record level, when recording at ± 40 percent of the nominal carrier frequency, is defined as the rms voltage of a sinusoidal input signal, at a frequency up to 0.1 times the nominal upper cutoff frequency, that produces no more than 1 percent distortion in the third harmonic of the output signal.)

- (2) The variation in amplitude/frequency response at the standard record level should not exceed ± 0.5 dB, relative to the response at 250 Hz, over the frequency range from dc to 10 000 Hz. (The standard record level is defined to be an rms voltage at the input to the tape recorder that corresponds to a voltage 10 dB below that for the maximum record level.)
- (3) The variation in tape speed throughout the duration of any reel of tape should not exceed ± 0.005 percent of the nominal tape speed.
- (4) The multiple-channel tape recorder should have enough recording channels to accommodate all the microphone systems, and a tape-speed-control reference frequency. Voice annotations and time code signals should be recorded on edge tracks.

The tape recorder should be capable of being operated on ac or dc power. Operation in the field on 115 V, 60 Hz, ac power is preferred because of the problems with varying battery voltage for various ambient temperatures and the varying charge level of the battery electrolyte for a full-day's operation. As indicated in figure 9, the ac power can be supplied by a small generator designed to operate at low speed, providing it is lightly loaded and is well muffled so that the noise of its operation does not interfere with the flyover noise recordings. Batteries should be available for use in emergencies. Rechargeable batteries are recommended.

The signal-conditioning equipment at the input to the tape recorder should include step attenuators. The recommended interval between steps should be 5 dB to provide enough flexibility to keep the input voltage close to the desired nominal value. The accuracy of each 5 dB step should be ± 0.1 dB or better. A range of amplifier gain adjustment of at least 50 dB should be provided for each data channel.

A wideband rms voltmeter, oscilloscope, frequency counter, and multiple-channel strip-chart level recorder should also be provided to monitor signals at the input to the tape recorder. The oscilloscope and frequency counter will be particularly useful in monitoring the output of the acoustical calibrator used to provide a reference sound level. The strip-chart level recorder is used to monitor the A-weighted and wideband (linear)

ambient noise levels at the microphones (checking compliance with the maximum recommended ambient noise levels) and to determine when to terminate the recordings of aircraft noise signals. The frequency response and meter-ballistics/detector-averaging characteristics should comply with those specified for the type I sound-level meter requirements of reference 30. The strip-chart level recorder should have at least six channels with each channel having a range of at least 20 dB, and preferably 30 dB. Different color inks may be required to identify the separate traces. Reference 45 provides a broader discussion of data-monitoring requirements during testing of airplane flyover noise.

The tape recorder and associated equipment should be installed in an appropriate vehicle such as a van. No air conditioning or environmental control is required in the van for the instruments because of the limitations in figure 4 on temperature and humidity, although hot and humid conditions may introduce problems with the recording tape and may cause some excessive head wear. Note, however, that there will be minimum drift in the operation of the recorder if the ambient temperature in the van is kept approximately constant.

Calibration. - It is important to distinguish between calibration of a system (or its components) and checking performance. This section describes requirements for instruments used in the field for calibration.

Calibration is defined as the determination of the behavior of a measuring system to a known signal for the purpose of evaluating subsequent measurements and correcting for characteristics that are not ideal. A system check is defined as a verification that the behavior of a measuring system is within certain defined limits.

An additional distinction is required between field and laboratory calibration. Laboratory calibration is performed for all relevant components of the microphone system (fig. 6) and the data-recording system (fig. 9). Laboratory calibrations include determination of the frequency response of system components, and the absolute sensitivity of a microphone (at various frequencies and angles of incidence). Laboratory tests are conducted to ascertain that the performance characteristics of a system component are

within the manufacturer's tolerance. Laboratory calibration determines the effects of various temperatures, humidity, and pressure. A laboratory calibration procedure is required to evaluate the performance of such components as windscreens and determine the effect of a windscreen on sensitivity over the range of frequencies and angles of incidence for winds of various speeds and directions relative to the microphone axis. The noise reduction provided by the windscreen would be determined in the laboratory as a function of frequency for various wind speeds and wind directions relative to the microphone axis.

Although laboratory calibrations are required to support the field data acquisition program, specifications of performance requirements for instruments for laboratory calibrations are not given here. Laboratory determinations of the characteristics and absolute accuracy of the instruments used for field calibrations and any requirement for traceability of performance determinations by a national standards laboratory (e.g., the U.S. National Bureau of Standards) will be carried out as part of a laboratory procedure.

With the above understanding of the differing roles of laboratory and field calibration, the functions of field calibration are fourfold: (1) determination of an acoustical reference level; (2) determination of electrical background noise level, (3) determination of system frequency response, and (4) determination of the amount of drift, if any, in system sensitivity that occurs during the course of testing. Figure 10 illustrates the components required to accomplish these functions for one data-recording channel.

An acoustical calibrator of the microphone coupler type is placed over the microphone in such a way as to provide a tight seal around the microphone. By electromechanical means, the calibrator generates a known acoustic pressure inside the enclosed volume over the microphone diaphragm. A sinusoidal signal with a frequency in the flat portion of the microphone system's frequency response is preferred. A nominal frequency of 250 Hz is recommended. The sound pressure level incident on the microphone diaphragm should be high enough to be well above the ambient noise level and also above the maximum expected value of the aircraft noise signal at 250 Hz. The value of the incident calibration signal should be known within a small tolerance. The level and the waveshape of the output of the acoustic calibrator should be

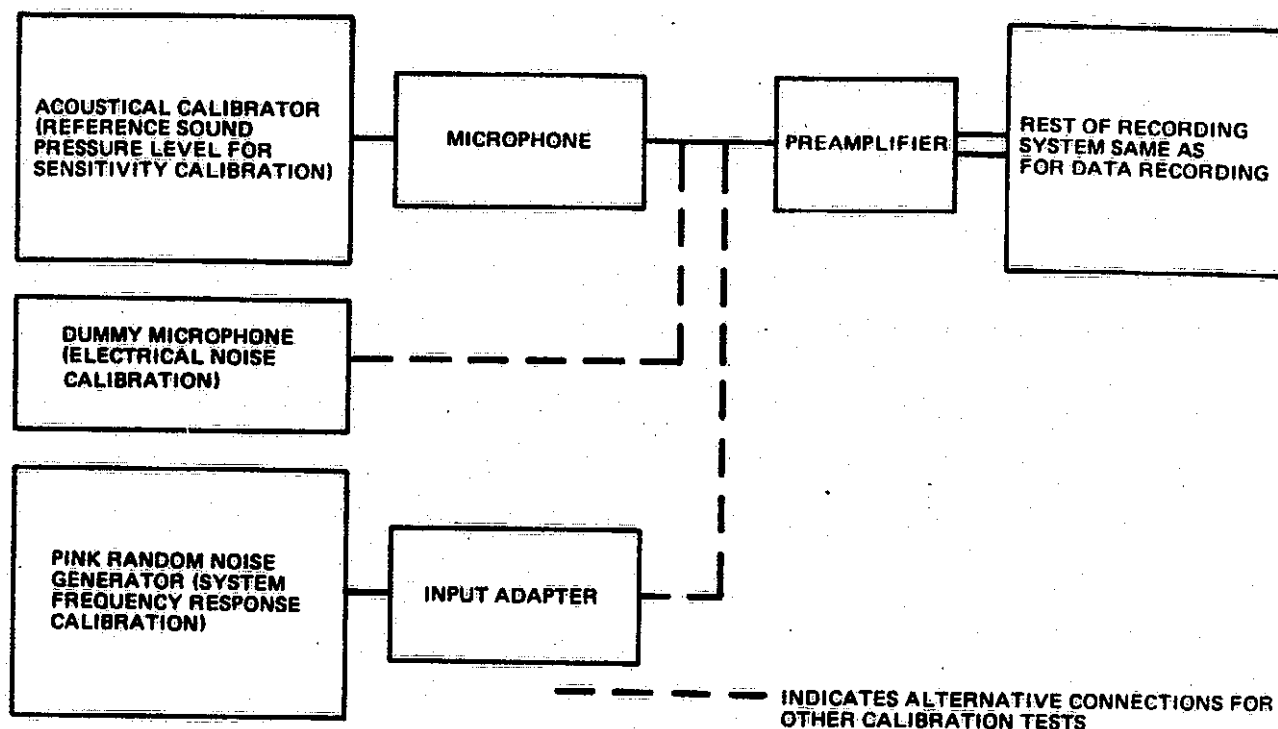


Figure 10. -Components required for field calibration of acoustical sensitivity, electrical background noise, and system frequency response of one data-recording channel.

independent of temperature and humidity over the range from -10° to $+40^{\circ}\text{C}$ and 20 to 95 percent relative humidity. The effects of atmospheric pressure should be known and should be minor for the range of atmospheric pressure likely to be encountered. The calibrator should be battery-powered and the level, frequency, and waveshape of the output should be essentially independent of battery voltage until the batteries are almost unable to supply additional current. A sound pressure level of $124.0 \text{ dB} \pm 0.2 \text{ dB}$ as a common value for the level and accuracy of the reference sound pressure level. Drifts in sensitivity are checked by repeating the reference sound-level test.

While the reference sound level is established with the microphone in place on the preamplifier (windscreen removed), calibrations of system self-noise and system frequency response are performed with the microphone removed from the preamplifier. The dummy microphone mounts directly on the preamplifier. The only requirement (other than mechanical) is that the dummy microphone have the same nominal electrical impedance as the actual microphone.

System frequency response can be determined using sinusoidal or random signals. Random signals are preferred because aircraft noise signals are predominantly broadband random in character. The preferred frequency spectrum of the random noise should be that of "pink" noise with a spectrum level slope of -1 dB per 1/3-octave band (a band-level slope of 0 dB per 1/3-octave band). A pink noise spectrum is preferred over a "white" noise spectrum (spectrum level slope of 0 dB per 1/3-octave band) because most aircraft sounds slope off at high frequencies and because a band analysis of pink noise is conveniently flat.

The wideband output voltage (bandwidth at least 20 to 20 000 Hz) should be at least 5 mV rms. Output voltages greater than 5 mV rms are acceptable if attenuators are provided on the generator to reduce the voltage to approximately 5 mV. The value of the rms output voltage should be known. The probability density function of the amplitude of the output of the pink-noise generator should be approximately that of a normal or Gaussian distribution for any 1/3-octave band with center frequency between 50 and 10 000 Hz.

A popular instrument for producing an approximate pink (or white) noise spectrum uses a shift register to generate, with feedback, a train of binary voltages (pulse train) occurring at almost randomly varying times. Transitions between voltage levels only occur at the pulse times of an internal clock. The output of the shift register is a known sequence of binary ones and zeros that repeats after a fixed number of clock periods. The length of the binary sequence is $2^n - 1$, where n is the number of shift-register stages used to generate the sequence. One instrument uses 20 shift-register stages giving $2^n - 1 = 1\,048\,575$ clock periods. The probability density function of the sum of all the pseudo-random binary signals from the shift register is almost truly Gaussian.

The output of the shift registers is applied to a digital-to-analog converter forming a low-pass digital filter. The cutoff frequency of the filter is determined by the number of shift registers used to define the length of the binary sequence and the frequency of the internal clock. For a clock frequency of 520 kHz and 20 shift registers, the 3-dB cutoff frequency is 26 kHz, an adequate value for aircraft flyover noise testing.

The power spectrum of the output of the digital-to-analog converter is flat from dc to about 15 kHz, ± 0.3 dB, i. e., an approximately white noise power spectrum. The spectrum is not continuous but rather consists of a series of closely spaced spectral components of random phase. The spacing between spectral components is the ratio of the clock frequency to the length of the pseudo-random binary sequence. In our example, the frequency spacing would be 520 000/1 048 575 or about 0.5 Hz. Thus, in the lowest 1/3-octave band of interest (centered at 50 Hz) there will be about 25 spectral components. All the other bands will have more components because the components are evenly spaced but the bandwidths increase.

Pink noise is produced by filtering the white noise signal through a resistance/capacitance network. With the pink noise signal, low-frequency response does not extend to dc but to approximately 1 to 3 Hz. The output voltage indicated by the generator is a wideband rms value consisting primarily of low-frequency energy with peak amplitudes up to 3.5 times the mean value.

If available, the pink-noise generator should be battery-powered with a stable output. The output of the generator should be independent of temperature and humidity over the range from -10° to $+40^{\circ}$ C and 20 to 95 percent relative humidity. The output of the generator should also be essentially independent of battery voltage. If a battery-powered pink-noise generator is not available, it will be necessary to provide an inverter to produce the required ac power. The inverter can be one that operates from a 12 V battery in a car or truck which is driven to each microphone location. Typical requirements for the inverter will be to provide 115 Vac, 60-Hz, single-phase regulated power for a maximum current drain of 0.5 mA rms.

As indicated in figure 10, a special input adapter may be required to insert the voltage from the pink-noise generator into the microphone pre-amplifier. Note, however, that the system frequency response calibration indicated in figure 10 is not an insert voltage calibration. Insert voltage calibrations are performed in a laboratory with the microphone mounted on a special preamplifier and with a voltage from an oscillator or random noise generator applied across a resistor in series between the capacitance of the

microphone and the preamplifier. The output of the pink-noise generator for calibrating the system frequency response is applied directly to the microphone preamplifier with the microphone removed. Thus, the pink-noise generator is part of a system frequency response calibration, not an insert voltage calibration.

Airplane and Engine

Various types of calibrated instruments are required to measure and record the airplane and engine parameters needed for subsequent data analysis. The measurements should be continuously recorded along with time code information.

There are many methods available for recording the necessary information in the desired format. The methods include a cockpit photo recorder (movie camera), a special test photo recorder not located in the cockpit, devices to record analog voltages from the cockpit instruments (such as oscillographs and magnetic tape recorders), and devices to record digital voltages (digital magnetic tape recorders). Digital data systems are preferred over analog systems because the digital magnetic tape recordings can be made directly compatible with processing by a digital computer. It is desirable to supplement the continuous recordings with periodic samplings by the flight crew of the readings of the cockpit instruments. The supplemental observations can be recorded on preprinted forms on a clipboard.

A movie camera would be mounted in the cockpit so as to photograph the instruments of the pilot, copilot, and, if present, the flight engineer, and a calibrated, synchronized clock. Two cameras may be required. The disadvantages of cockpit cameras are that the view of some instruments may be distorted, portions of the flight crew's bodies can obscure some of the instruments, and the film record must be transcribed. Transcription of several parameters from several tests is tedious, time-consuming, and expensive. Furthermore, there is limited opportunity for a nonmember of the flight crew to monitor airplane or engine performance parameters.

For the preferred digital data system, analog signals from the cockpit instruments are converted to a digital format and recorded on a digital

magnetic tape recorder. The digital tape recording is then read and processed under control of a digital computer as part of the data-processing task. Data can be sampled and recorded at a high rate such as every 0.01 to 0.2 sec. The recording must include time code information from a time-code generator that has been synchronized with the time-code generators at the ground recording stations.

The airborne digital data system should be flightworthy and compatible with the requirements of the test aircraft. It should be capable of being operated from available aircraft power. There must be no interference with the operation of any of the instruments being monitored.

No special instruments are normally required to measure airplane or engine parameters. Instruments normally installed in the airplane should be adequate to measure all the necessary parameters. All instruments, however, should be calibrated and checked, by procedures recommended by the aircraft manufacturer, prior to flyover noise testing.

Airplane parameters that should be measured include: indicated airspeed; indicated Mach number; gross weight; altitude (above mean sea level); angle of attack (if available); pitch angle; climb gradient or rate of descent; nominal deflection angle for trailing edge flaps; indication of deployment of wing leading-edge devices, spoilers or speed brakes, and landing gear; and the outside total temperature and ambient pressure.

Parameters that should be measured for each engine include: shaft speeds, engine pressure ratio (ratio of the total pressure in the engine inlet to the total pressure in the gas-generator exhaust nozzle or downstream of the last turbine stage), engine exhaust gas temperature (in the gas-generator exhaust nozzle or downstream of the last turbine stage), and fuel flow rate. For turbofan engines having a single common mixed-flow exhaust nozzle, the discharge or exhaust gas temperature and pressure should be those for the primary gas-generator exhaust gas before mixing with the fan-discharge flow.

Instruments installed to measure the above-named airplane and engine parameters should be able to provide data with the usual accuracy and resolution of aircraft instruments. Accuracies that should be achievable for meas-

urements of pressure, temperature, and shaft rotational speed are ± 0.2 percent of the full-scale reading, $\pm 1^\circ$ to 2°C , and ± 10 rpm, respectively.

If the test objectives require measurement of airplane or engine parameters other than those listed above, it will be necessary to install special transducers and instruments to record those parameters. Examples of such parameters might include: engine inlet total temperature, fan discharge temperature or pressure, combustor exit temperature or pressure, and pressure drop across the turbine stages. Accuracies achievable by the special instruments should be comparable to the accuracies available from the standard cockpit instruments.

Airplane Space Positioning

Various techniques have been used over the past two decades to determine the position of an aircraft relative to the microphones. The techniques have included photographing the airplane with still cameras from each microphone location (or at a representative location if the airplane could be assumed to fly a known flight path) at the instant of time when the airplane was, visually, closest to the photographer. Ground-mounted motion-picture cameras have also been used. Distance at the time of closest approach was then calculated using the laws of similar triangles knowing the focal length of the camera and the actual length of some aircraft component seen in true perspective and the length of the same component in the photographic image. Photographic scaling techniques are not considered suitable for ANOPP fly-over noise tests because the only information directly provided is the minimum distance at a single instant of time.

A phototheodolite (tracking telescope) can be used to provide information on the time variation of the location of the aircraft. The phototheodolite records horizontal angles (azimuth or bearing) and vertical angles (elevation) on movie film. Range and position information are determined later by triangulation methods using a calibration obtained by photographing an object at a known distance, azimuth, and elevation. The theodolite must be stationed to the side of the flight path and the operator must attempt to track a target on the airplane (e.g., a main landing gear) as the airplane enters and

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leaves the test area. If a single theodolite is used, it is not possible to determine lateral deviation from the nominal flight path. Multiple theodolites are required to determine airplane x, y, and z coordinates throughout the duration of the noise recordings.

The principal disadvantages of most phototheodolite systems are the limitation on range to 5 to 6 km, the lack of on-line real-time data, and the tedious, time-consuming, and expensive task of transcribing data from the film record for use in subsequent data processing. The phototheodolite also can only be used when the operator can see the airplane. At night, or in the evening or early morning hours, the operator could track a light on the airplane.

Another tracking method that uses a motion-picture camera is described in reference 46. The method uses a 35-mm movie camera mounted on the bottom of the fuselage of an airplane and looking down. The camera is operated at 5 or 10 frames per second and photographs parallel rows of targets on the ground below the nominal flight path. The targets are typically 1.2-m square and are positioned on lines perpendicular to the nominal flight path. Three rows of targets are usually used. The target squares are typically about 15 m apart.

After the tests, the movie films are developed and the x and y coordinates of the targets are read by a mechanical film reader along with film frame times encoded by IRIG time code. Height above ground, the lateral deviation of the aircraft from the nominal flight path, and the time of closest approach to each microphone are then calculated from the x, y, and time code data and airplane attitude data. Airplane attitude data must include pitch and roll angles, but not necessarily yaw angles.

The shortcomings of the airborne movie camera system are: the requirement to install the downward-looking camera and associated equipment in the airplane, the need to survey in and install the targets, and the lack of on-line airplane position data. The film records, however, can be read mechanically (with operator assistance), in contrast to the cockpit camera method, although it is still tedious and time-consuming. The

camera must be able to see the targets, thus effectively restricting the times when tests can be conducted to the daylight hours.

The best, but relatively expensive, method capable of providing complete information on aircraft space position is tracking by radar or laser (optical radar). The transmitter can be mounted in the aircraft or in a tracking van on the ground. The ground location is preferred so that the major part of the system can be independent of the airplane. A laser system is preferred over a radar system because it can achieve better resolution and accuracy of range and angular coordinates than a radar system, especially for large aircraft. One technique that has worked well makes use of an array of retroreflectors mounted in some convenient location on the airplane and a laser tracking system installed in a mobile van (refs. 32, 47, and 48). Leveling jacks are provided to support the van and the laser tracking pedestal independently of one another so that operator movements do not affect the accuracy of the results.

The retroreflectors have internal mirrors arranged to return the laser pulse to the tracker with high efficiency. The echo return pulse is strong enough to be detectable in bright daylight illumination. The retroreflector arrays are relatively small, lightweight, and quite rugged. A variety of units have operated in all kinds of airborne environments.

The output of the laser tracking system is a stream of digital information at sample rates up to 100 measurements per second on aircraft position (range, azimuth, and elevation) and a synchronized time code signal. Calibration of the system is provided by measuring the distance to a target at a known range, azimuth, and elevation.

The main advantages of laser tracking systems are: the high accuracy of the results, the ability to track the airplane at night or in the evening or early morning hours, the relative ease of setup; the independence from the airplane (except for the retroreflectors); the elimination of the need to transcribe a film record; and the provision of on-line data. Furthermore, unlike other systems, the laser tracker can operate into the direction of the sun. Note also that the study reported in reference 46 recommended a laser tracker for aircraft noise research testing.

The x, y, and z coordinates of a reference point on the airplane are related to the coordinates of each microphone, as a function of time, during data processing. Airspeed can also be determined. The reference point on the airplane will probably not be the location of the retroreflectors, but will be some point (or points) more closely associated with the aircraft noise sources such as the center of an engine inlet or an engine exhaust plane.

A portable, quiet generator of ac electrical power should be provided so that operation of the tracking van can be independent of the acoustical and meteorological measurements. The tracker must have the ability to automatically record space position data in a format compatible with subsequent processing by a digital computer. The recording should be on digital magnetic tape and should include an IRIG time-code signal synchronized with the IRIG time-signals being simultaneously recorded with the acoustical data and the airplane and engine data. Real-time analog data could also be provided in a suitable format.

The tracker should be equipped with a system for manual initial acquisition of the retroreflector target. The operator should have a joystick to permit manual slewing of the laser transmitter/receiver pedestal while observing the airplane on a television screen. When the target is positioned in the central area of the field of view on the TV display, the system should then lock onto and automatically track the target until it is out of range or until data are no longer required.

The intensity of the laser beam should be automatically controlled, as a function of target range, to ensure that no damage occurs to anyone's eyes and to minimize power requirements.

The tracking system's capabilities should include:

- tracking ranges between 300 and 20 000 m;
- elevation angle coverage of -5° to $+45^{\circ}$;
- azimuth angle coverage of $\pm 120^{\circ}$; and
- position accuracy of ± 0.3 m for a range of 600 m and ± 5 m for a range of 10 000 m.

The 300-m lower limit on tracking range is set by the intensity of the echo return. For ranges less than 300 m the intensity of the return signal would saturate the receiver. Airplane heights of less than 300 m are easily tracked, however, by just displacing the tracking van to the side of the runway by 500 to 600 m.

The laser tracker does not provide airplane attitude data (i. e., angles of pitch, roll, and yaw). As with other external tracking methods, attitude data must be supplied from an onboard aircraft system such as a gyro or inertial navigation system. Attitude data, especially pitch and roll angles, are needed as a function of time to determine the coordinates of the retro-reflectors and the noise sources with respect to the microphone locations.

Meteorological

Instruments for meteorological measurements fall into two categories: those for measuring atmospheric conditions at a stationary location(s) near the microphone locations, and those for measuring atmospheric conditions as a function of height above ground level. As outlined above in the description of test criteria, the test program will include meteorological measurements both near the surface and aloft.

The crucial questions to answer with regard to selection of instruments and associated performance requirements are what is to be measured, where, with what accuracy and precision, and how often. The main parameters of interest are temperature, humidity, pressure, wind speed, and wind direction. With regard to wind, it is assumed that the vertical component can be neglected with respect to the horizontal component.

The properties and conditions of the atmosphere constantly have both small-scale and large-scale variations in temporal and spatial characteristics. Temporal variations can be short or long relative to the sound-propagation time between the aircraft and a microphone; spatial variations are short or long relative to the propagation path length.

For a given test, large-scale fluctuations can be considered essentially independent of time and the variation with height above ground level can be

represented by a relatively smooth profile of the mean value of a parameter. The profiles will change (relatively slowly) as a function of time during the day and from day to day, but they should be representative of the vertical variation in the region of the microphone array at any given time. The mean values should be long-term averages, at the surface and aloft.

Gradients in the profiles of mean temperature, humidity, and wind will bend otherwise straight propagation paths between the airplane and the microphones, and will modify the amount of atmospheric absorption and inverse-square spreading loss that would otherwise have occurred. The sound-propagation paths are bent by refraction effects because of changes in the speed of propagation caused by temperature and wind variations. Bending increases the path length and hence the atmospheric attenuation. If the conditions aloft are quite different than those near the ground, the atmospheric absorption losses can be quite different along different segments of the propagation paths. Note also that variation in mean conditions can be a source of variability for repeat runs. Measurements of atmospheric parameters at the surface and aloft must be able to evaluate the acoustical effects associated with changes in mean meteorological conditions.

Because temperature, humidity, and to a lesser degree, pressure are important to subsequent data adjustments, their measurement should be made with very accurate instruments. Wind information is used primarily for go/no-go decisions and likely will not be required in data processing or analysis except for labeling and perhaps for rationalizing anomalous results or to provide a reason for not using some of the data in subsequent analyses. Thus, accuracy requirements on wind measurements are not as stringent as those for temperature and humidity.

In all cases, for all five parameters, the output should be permanent records. For the data-processing system envisioned, it is not considered necessary to record meteorological data in a format directly compatible with machine processing. Strip-chart records, made by an ink pen or (preferably) electrical means, are adequate. Throughout each test day, the mean values of the atmospheric parameters can be manually transferred from the paper-trace records to data logs, tabulations, or graphs for use in

subsequent analyses. In conjunction with machine data processing, meteorological data can be entered manually by various means such as punched cards.

The instrument performance requirements described below for measuring meteorological conditions near the surface and aloft were developed in light of the above considerations and the earlier discussion of general instrument requirements.

Surface. Figure 11 illustrates the principal instruments and general arrangement recommended for surface meteorological measurements. Air temperature, humidity, wind speed, and wind direction are measured by instruments mounted on a tower located near the microphone array, but remote from the central recording van. The instruments should be about the same height above ground level as the microphones. The tower could be a hinged design similar to those recommended for the microphones. For a single location, however, it would be more reasonable to consider a tower mounted on a trailer.

A trailer-mounted tower has the advantage of portability in case it is necessary or desirable to sample surface data at different locations. The

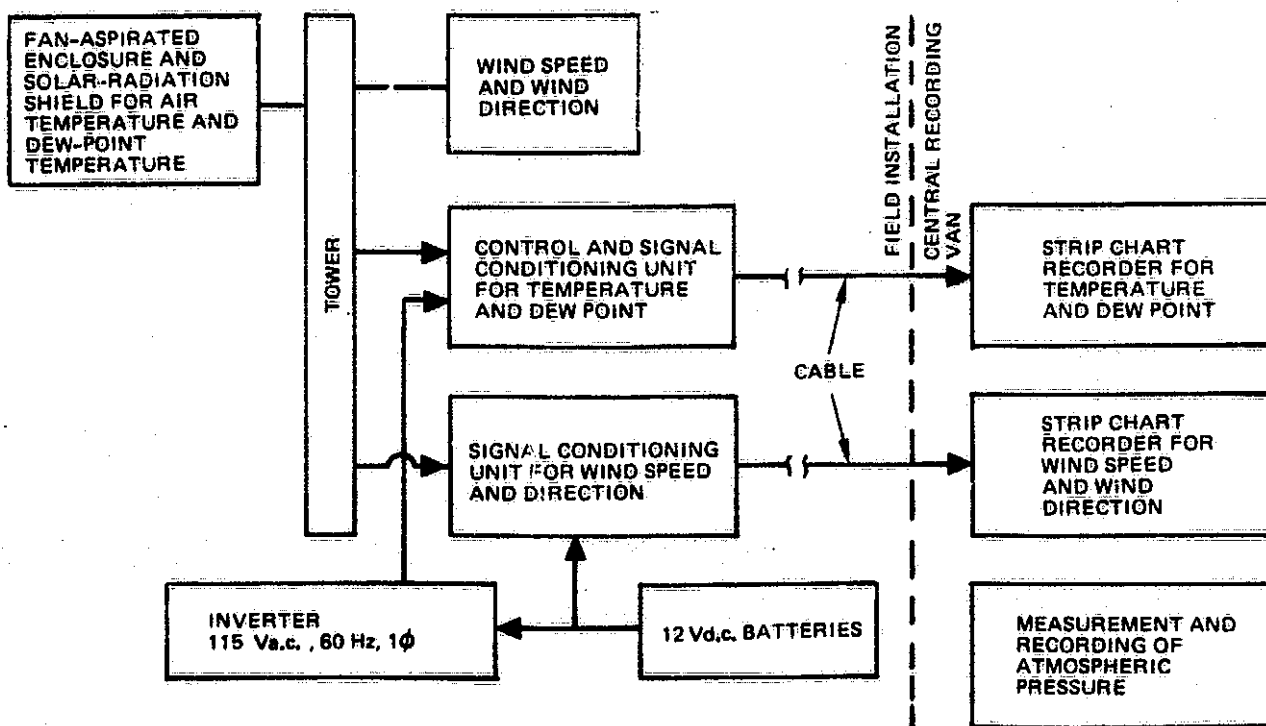


Figure 11. -Instruments for measurement of surface meteorological parameters.

tower would be a tilt-over, crank-up, telescoping design. It could be raised and lowered by a hand-cranked winch and cable with a worm-gear drive providing mechanical advantage. The tower probably could be free-standing with no guy wires. Outriggers could be attached to the trailer at the base of the tower, if necessary, for increased rigidity. An accessory box could be located at the front of the trailer in which batteries, inverter, signal-conditioning units, and reels of signal cables could be installed and secured.

The instruments should be mounted at or near the top of the tower on booms so that the sensing elements are one or two meters away from the tower. The booms should be sturdy and solidly attached to the tower so that the instruments do not sway back and forth in the wind. Two booms would be required; each boom should be capable of supporting a mass of 6 kg. A two-section tower is preferred over a four-section tower (for a height of 10 m) because of the greater rigidity, although the nested length will be somewhat greater with the two-section than with the four-section tower.

Since automatically recorded permanent records are needed, since the sensing elements are located in the air on a tower, and since a remote read-out of the instruments is desirable, the choices of instrument type and system are somewhat limited. The system shown in figure 11 is based on the transmission of analog voltage signals over hardwire signal cables from the remote instrument tower to the central data-recording station. It is advisable to locate the strip-chart recorder in the central data-recording station so that the operator can observe the development of trends as the basis for making go/no-go decisions relative to weather criteria.

A hardwire cable system is recommended because it is more reliable or less expensive than alternative arrangements. One alternative arrangement would be to locate battery-operated strip-chart recorders at the weather tower. Someone then could be stationed at the weather tower to monitor the strip-chart recordings and to relay, by two-way radio, the recordings to the operator of the central data-recording station. Readings would be transmitted when requested, but the minimum would be prior to each flyover noise recording.

A second alternative would be to use a radio telemetry system. The four channels of analog data could be converted to four channels of digital

data and transmitted by a single-carrier-frequency system using a multiplex technique with subcarrier frequency modulation. A telemetry receiver would be located at the central recording station with appropriate demodulators and digital-to-analog converters so that the four channels of analog data could be recorded on the strip charts.

Both of these alternatives eliminate the problems of laying (and picking up) the signal cables as well as the not insignificant cost of cable. The cable length could be 500 to 1000 m. The first alternative has the disadvantage of requiring another person. The second alternative has the disadvantage of the relatively high initial cost of a telemetry system as well as the disadvantage of requiring a considerable amount of electrical power in the field. Moreover, since cables are being laid and retrieved for each microphone location, it should not be much more effort to lay out and retrieve the cables for the weather tower. The same precautions should be observed with respect to rodent resistance, tensile strength, and salvage value as for the microphone cables. (We note here that for some situations it may not be feasible to lay out several thousand meters of microphone or weather-measuring cable [in residential areas for example] and the whole approach of using a central recording van would have to be abandoned. The recommended test site criteria for the ANOPP tests, however, should always permit the use of long signal cables.)

Cables for weather data do not have some of the concerns that microphone cables have. The signals being transmitted are dc voltages. Capacitance cable loading of the signal conditioning amplifiers causing high-frequency rolloff is not too important. The voltages being transmitted are 10 to 1000 times, or more, greater than the voltages from the microphones. The voltage drop across the cable will be relatively small if the cable is terminated in a high impedance. (The input impedance of strip-chart recorders is on the order of 100 000 ohms [or up to 10 M Ω for some recorders] compared to a cable resistance of 100 to 200 ohms.)

Humidity and temperature: The most critical instrument is that for the measurement of humidity. One technique used for many years for meteorological humidity measurements, where data are continuously recorded, relies on changes in the elongation of one, or two, bundles of

human hair as the humidity changes. Elongation changes are amplified by a system of levers and transmitted mechanically to an ink pen writing on a roll of chart paper. The instrument (known as a hygrograph) is enclosed by a shelter which is open to air currents. The accuracy of the human-hair humidity sensors is on the order of ± 4 to ± 5 percentage points around the indicated percent relative humidity. Nonlinearity in the humidity/hair-elongation relationship is partially accounted for by the mechanical linkage. Although the human-hair hygrograph does produce a permanent record, it would have to be installed at the top of the tower and would be unavailable for monitoring and thus would not be acceptable. Furthermore, the accuracy and resolution are both poor, the practical range of relative humidities does not extend below 10 or 15 percent, and the humidity/elongation characteristics change with time requiring periodic recalibration.

Another possibility would be to use a polymer thin-film capacitor installed in a probe. This arrangement, with suitable signal-conditioning equipment, produces analog dc voltages that can be transmitted over a cable. The accuracy of the thin-film capacitor arrangement is better than that of human-hair hygrographs, and is on the order of ± 2 to ± 3 percentage points around the indicated relative humidity. For outdoor measurements, the sensing element should be coated and sealed to reduce the corrosive effect of atmospheric pollutants, especially sulfur dioxide. The coating lengthens the useful lifetime, but also lengthens the instrument's response time. Because of the long response time, a thin-film capacitor is not considered adequate for aircraft noise research testing.

Sensors known as hygristors are also available. Hygristors use a film coating of a conducting and hygroscopic chemical such as a dispersion of carbon granules in a suitable binder. The resistance of the film varies with the water content of the sample of air to which it is exposed. Changes in the resistance of the film are proportional to changes in the relative humidity. Hygristors are not reliable below about 20 percent relative humidity. The accuracy of standard carbon hygristors is on the order of ± 5 percentage points around the indicated percent relative humidity; premium grade hygristors are available, however, that have been specially selected from a

given production batch such that the accuracy is within ± 2 percentage points of the actual relative humidity.

Hygristors have been used routinely on a daily basis for more than 25 years at meteorological stations around the world. Being small and lightweight, they are suitable for balloon-borne radiosonde probing of humidity profiles in the lower atmosphere. The sensing element must be shielded from solar radiation, and it should be aspirated, either naturally or, preferably, with a blower. Aspiration is required to reduce the response time to large changes in humidity (such as occur, for example, when entering or leaving a cloud or fog layer); the usual procedure is to use natural aspiration and the response time can be quite long.

Consistent with their intended application, hygristors are inexpensive and have short lifetimes. Some sensitivity is irretrievably lost every time the film stretches or contracts in response to changes in humidity. They do, however, operate well for a single ascent as part of a radiosonde system where the instrument package may not be recovered, or where the hygristor element would be replaced should the instrument package be recovered. For a tethered-balloon system, the hygristor element can be used for several ascents and descents until the hysteresis, or difference, in readings between ascents and descents, or between repeated ascents, becomes too large. The element should then be changed. Hygristors are not considered suitable, however, for surface measurements of humidity on a stationary tower for several hours each day.

The recommended instrument for humidity measurement is one that separately measures both the dew point temperature and the ambient temperature of a sample of the atmosphere. Relative humidity (or any other humidity measure) can then be calculated from the two temperature measurements.

Measurement of dew point temperature (or dew point, for short) must be accomplished in such a way that the pressure and temperature of the sample of air are not modified, and that moisture is neither contributed to nor absorbed from the sample. The materials used in the instrument must be nonhygroscopic, particularly for low-humidity conditions when the dew point is less than -10°C .

The recommended technique for measuring dew point is one that makes use of a fundamental or primary procedure such that no calibration is required. Such a technique is one in which a metallic mirror is automatically controlled by an optical system to maintain a constant surface reflectance. The chosen reflectance is a fraction of that of a clean dry mirror surface. The surface of the mirror can be cooled (not heated) by a thermoelectric cooler using the Peltier effect. When the reflectance is higher than the chosen value, an electronic circuit activates the thermoelectric cooler. When the reflectance is lower than the chosen value, the mirror is not cooled. Thus, when the mirror is exposed to a flow of air containing some amount of moisture, it will cool until enough water is condensed out of the air stream to achieve a constant reduced value of reflectance of visible light from the surface of the mirror. The mirror surface temperature is maintained at the equilibrium temperature such that the rate of evaporation from the surface water (or ice) is equal to the rate of condensation. This equilibrium temperature is the dew point (or frost point). Even minute changes in the humidity content of the air stream will upset the equilibrium condition and, in time, can be detected. (The dew point temperature is that temperature to which the air must be cooled [at constant pressure and mixing ratio] such that it is saturated with respect to water; frost point temperature is that temperature to which the air must be cooled such that it is saturated with respect to ice. The instrument measures frost points when the humidity is such that the temperature depression causes the temperature of the mirror to fall below 0°C.)

Measurement of dew point temperature must be accompanied by a measurement of air temperature. Accurate measurement of these temperatures can be made using platinum resistance thermometers. The output from the temperature measurements is scaled by a calibrated signal-conditioning circuit to provide dc voltages from 0 to 5 Vdc. The range of output voltages corresponds linearly to some selected temperature range, for example, 0 to 5 Vdc can correspond to -50° to + 50°C, or a scale factor of 50 mVdc per degree C.

The dew point and the air temperature sensors should be enclosed within a shelter or shield that is aspirated by a small, quiet fan blower.

The instruments should be upstream of the fan so that they do not sense any temperature rise or any contaminants (such as hydrocarbons from greases or oils) in the fan exhaust. The fan should preferably be located above the temperature/dew point sensors.

The enclosures should have a low-emissivity finish and a white color so that the sensors are shielded from direct heating by solar radiation.

The enclosure and all materials used in construction of the instrument should be inert and resistant to atmospheric pollutants (chemicals and smog) and salt in locations near an ocean.

Dirt and dust particles can collect on the mirror and change the reflectance. The instrument should have a built-in capability for checking the design-point reflectance and determining the need to clean the mirror. The design should permit easy access for cleaning when required.

Recommended key performance parameters are:

- accuracy of temperature measurements should be no worse than $\pm 0.3^{\circ}\text{C}$ over the full range of temperature;
- dew point depression capability (below the temperature of the air) should be at least 55°C for temperatures above 25°C ;
- dew point depression capability for temperatures less than 25°C should decrease no faster than 0.6°C for each 1.7°C lowering of the mirror temperature below 25°C . (At an air temperature of -10°C , the dew point (or frost point) depression capability should not be less than 43°C);
- capability should be available to measure relative humidity over the range from 100 percent to less than 1 percent at any temperature within the operating range;
- sensitivity of the temperature sensing elements to changes in the temperature of the air or the mirror should not exceed $\pm 0.06^{\circ}\text{C}$; and,
- the aspiration air-flow rate through the protective solar-radiation shield/enclosure should be at least $0.03\text{ m}^3\cdot\text{s}^{-1}$.

The accuracy of the calculated values of relative humidity depends on the air temperature and the amount of dew point depression. When the humidity is low and the dewpoint depression is high, then the accuracy of the calculated relative humidity will be between ± 0.3 to ± 1.5 percentage points for the range of conditions likely to be encountered. When the humidity is high (say above 90 percent relative humidity), then the dew point depression will be small and the accuracy of the calculated relative humidity will be approximately ± 3 to ± 5 percentage points. Note that if the air temperature is less than 0°C , the saturation vapor pressure must be that over water and not over ice, in accordance with the definition of relative humidity.

An instrument that meets these performance requirements and has the other characteristics described above may not be battery-operated and may require 115 V, 60-Hz, single-phase ac power. If ac power is required, it is recommended that it be obtained by inverting dc power from standard wet-cell batteries as indicated in figure 11. A small engine-driven ac generator, while acceptable for use at the central recording van, is not recommended for use at the weather tower because it might increase the ambient noise level at the microphones. The inverter may have to supply on the order of 130 VA of ac power. With an allowance for an idle current of 9 A and assuming an average battery voltage of 11 V between fully charged and discharged, the battery will have to supply about 235 VA or about 21 A. To provide the capacity needed for 10 h of continuous, unattended operation, it is recommended that three batteries be connected in parallel, each having a current capacity of approximately 90 ampere hours. The batteries can be heavy-duty car or truck batteries. For temperatures lower than 10°C , four batteries may be required to make up for reduced battery capacity at low temperature.

The batteries should be recharged after each test day and spare, fully charged batteries should be available for a series of full-day operations. A battery charger will have to be available at a support facility. A supply of distilled water should also be available if required for topping up the battery electrolyte during the test period.

Several commercial inverters are available. A model should be selected that produces regulated power with an approximately sinusoidal waveshape

and at a nominal frequency of 60 Hz. The inverter may produce a hum due to magnetostrictive forces in the laminates of a transformer. Noise may also be produced by a cooling fan used to dissipate heat and increase operating lifetime. The quietest inverter meeting the requirements is preferred. It is also recommended that the inverter be mounted inside a vented enclosure, such as an accessory box on the tower trailer, to provide weather and security protection as well as some noise reduction.

The batteries should be enclosed in weather-proof enclosures and should be tightly strapped to the trailer to avoid spilling electrolyte. Aircraft-style spill-proof batteries could be used.

Wind speed and direction: Remote measurement of wind speed and wind direction is not nearly as complicated as remote measurement of temperature and humidity. Two simple systems are available for measuring wind speed: a propeller and a cup anemometer, each of which is mounted on a shaft to drive a generator or a tachometer with an output proportional to rate of rotation and hence proportional to wind speed. The standard three-cup anemometer works well in horizontal winds; updrafts and downdrafts give spurious or erratic readings. Sonic anemometers are also available that can yield vertical and horizontal wind components, but they are much more elaborate and complex than the propeller or cup anemometer as well as being almost an order of magnitude more expensive. Since wind data are only used in a qualitative fashion, the accuracy, resolution, and precision of sonic anemometers are not required for surface measurements. Wind-aloft data will likely not be as accurate or precise as the surface wind data; there is no need, therefore, for trying to obtain highly accurate surface wind measurements.

A lightweight aerodynamic vane is always incorporated with the propeller to keep the propeller facing into the wind and to measure the direction from which the wind is blowing. The vane is mounted on either an ac selsyn generator or a potentiometer. The selsyn (or synchro) generator is electrically linked to a corresponding selsyn motor such that the angular position of the generator shaft corresponds to the angular position of the motor shaft. The selsyn system is used to provide a visual indication of wind direction with a needle and dial attached to the motor shaft.

The potentiometer system is preferred because the varying dc voltage is directly suitable for transmitting a signal over a cable. The potentiometer should be of the continuous, conducting-plastic type to provide better resolution and longer lifetime than wirewound potentiometers. A total resistance of 1000 ohms should be adequate. The potentiometer should have two wiper arms to eliminate a dead region near magnetic north and to provide the capability for a range of wind directions from 0° to 540° . This expanded capability prevents painting the strip-chart recording when the wind direction is oscillating out of the north (swinging from 0° to 360° and then back to 0° with a single-wiper 0° -to- 360° system).

If a cup anemometer is used, the vane may be mounted separately away from the rotating cups or it may be mounted on a coaxial concentric shaft below the rotating cups.

The choice between a cup anemometer system and a propeller system is on the basis of the desired starting threshold (how light can the wind be and still give reliable readings?) and on considerations such as ruggedness and fragility. Costs are approximately equal. The accuracy of the cup anemometer is inherently better than that of propellers. In the range of wind speeds from 1 to $10 \text{ m} \cdot \text{s}^{-1}$, cup anemometers have accuracies on the order of $\pm 0.07 \text{ m} \cdot \text{s}^{-1}$ while propellers have accuracies on the order of $\pm 0.3 \text{ m} \cdot \text{s}^{-1}$.

Cup anemometers are available with cups made from various materials, including metallized butyrate, polycarbonate plastic, and stainless steel, in order of increasing weight. Stainless steel cups are preferred because of the requirement to periodically put up, take down, and transport the instrument. The starting threshold with stainless steel cups is about $0.4 \text{ m} \cdot \text{s}^{-1}$. One disadvantage of cup anemometers is that they are a favorite of "target shooters" because they spin readily when struck by a bullet.

Three-blade and four-blade propeller systems are available. They are typically made from fiberglass-reinforced plastic and are considerably more rugged than cup anemometers. The threshold where full tracking of the wind speed is obtained is about $1.5 \text{ m} \cdot \text{s}^{-1}$. The propeller does not offer the kind of target that cup anemometers do; it has a small frontal area and does not spin readily when struck by a bullet from the side.

For aircraft noise testing, the primary range of interest for wind speed is between 2 and 10 $\text{m} \cdot \text{s}^{-1}$. Wind speeds of less than 2 $\text{m} \cdot \text{s}^{-1}$ are of little consequence in self-noise at the microphones. Moreover, wind screens over the microphones should eliminate wind noise problems for low wind speeds. A threshold of 1.5 $\text{m} \cdot \text{s}^{-1}$ should therefore be adequate.

Thus, on the basis of its intended use and the considerations described above, it is recommended that wind speed and wind direction be measured with a combination of a propeller and tail vane. The accuracy of the wind speed measurement should be no worse than $\pm 1^\circ$.

There are three choices for translating propeller shaft speed to an electrical output signal: an ac generator, a dc generator, and a high-frequency tachometer. The ac generator is a long-life brushless design, but it does require a rectifier and only has an output voltage that increases linearly with wind speed above a minimum value on the order of 2 to 3 $\text{m} \cdot \text{s}^{-1}$. For the ac generator, the starting torque has to overcome friction in the bearings and the drag caused by the tendency of the armature to want to come to a stop lined up with the pole pieces of the surrounding permanent magnet. The dc generator (or magneto, since permanent magnets are used for pole pieces) provides a linear output down to low wind speeds, but requires brushes and therefore has a shorter lifetime and a higher starting threshold than the brushless ac generator because of the torque required to overcome the drag of the brushes.

The high-frequency tachometer uses a notched metal disc mounted on the propeller shaft. The disc is fixed so that it can rotate between a transmitter and a receiver in a solid-state oscillator circuit. As each notch passes between the transmitter and receiver, a square pulse appears at the oscillator output. The pulse height is approximately equal to the applied voltage, e.g., about 12 Vdc. The number of pulses per revolution of the propeller is equal to the number of notches on the disc. The oscillator system should be fully encapsulated to make it insensitive to moisture or dirt and dust. The lifetime should be very long since there are no parts to wear out except the bearings supporting the propeller shaft.

The pulse repetition rate is directly proportional to shaft speed and hence to wind speed. The threshold wind speed should be about $1.5 \text{ m} \cdot \text{s}^{-1}$. The pulse repetition rate is converted to a dc voltage by a signal-conditioning unit for transmission to the strip-chart recorder.

Another tachometer system is available that uses a notched disc to chop a beam of visible light. The pulses of light are detected by a photoelectric device and appear as a pulse train at the output. The system works well except that the light bulb can burn out and therefore is not as reliable as the all-solid-state system. (Note, however, that some light chopper systems use a solid-state light source for improved reliability.)

It is recommended that the high-frequency solid-state tachometer system be selected to sense wind speed instead of an ac or a dc generator or a light chopper system.

The selected instrument should be capable of all-weather operation and should be made from corrosion-resistant materials such as reinforced fiberglass and plastic. The signal-conditioning unit should use solid-state components. The system should be capable of operating on battery power, as indicated in figure 11. The current drain should not exceed 30 mA from a 12-Vdc supply and thus should easily be supplied within the capacity of the batteries used to drive the inverter for the power to operate the humidity/temperature system. The output of the signal-conditioning unit should have a dc output voltage of 0 to 5 V for both wind speed and wind directions. The unit should have a built-in system for self-calibrating wind speed against output voltage.

Air pressure: A simple barograph is recommended for measuring and recording atmospheric pressure. The barograph can consist of an aneroid barometer linked by levers to an ink pen writing on a roll of preprinted paper with appropriate scales. The aneroid element should be adjustable to permit operation at the elevation of the runway.

The chart can be rotated under the pen by either a spring-wound clock drive or a small electric motor powered by a standard 1.5 V D-cell battery. Rotation rates of one revolution in either 24 h or 7 days should be provided.

The barograph may be mounted inside the central data-recording van if the ambient air temperature permits a door or window to be left open. The instrument may also be mounted outdoors in a simple instrument shelter to shield it from solar heating and winds.

The following performance parameters are acceptable for aircraft fly-over noise testing. It is recommended that atmospheric pressure be recorded in millibars (mb).

- accuracy of ± 0.2 mb over a range of pressures from 945 to 1045 mb;
- resolution ± 0.3 mb
- sensitivity ± 0.3 mb
- operating range: sea level to 3600 meters

Miscellaneous: It will be convenient to have available two additional instruments. These instruments are relatively inexpensive and do not have the range of accuracy of the instruments described above. Also, they do not yield permanent records until someone reads them and notes the indicated values.

The instruments are (1) a fan-aspirated wet-bulb/dry-bulb psychrometer, and (2) a small, hand-held wind meter of the venturi type.

The fan on the psychrometer can be driven by either a wind-up spring or a battery-powered dc motor. A supply of distilled water should be available for the wick on the wet bulb thermometer.

These instruments can be used to obtain a check on the operation of the more-accurate instruments on the weather tower and for emergency backup measurements should the tower instruments fail to operate. The psychrometer is only useful for temperatures above 2°C and for relative humidities greater than 20 percent.

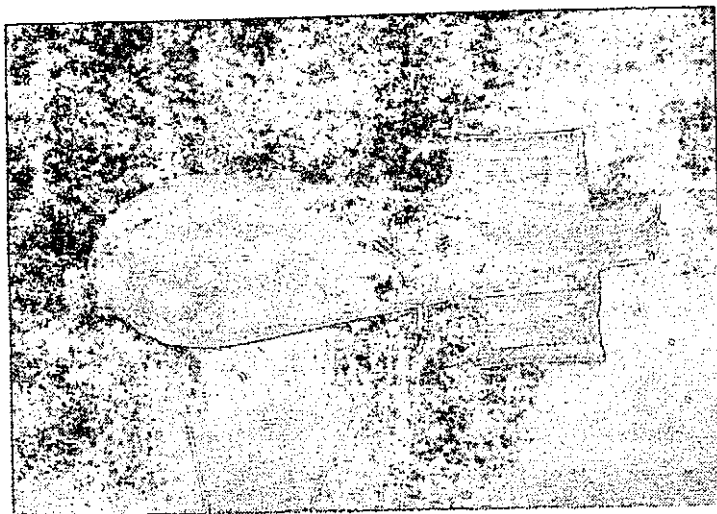
Aloft. - Specification of performance requirements for instruments to measure weather aloft is somewhat more difficult than for surface measurements. There are four systems that can be used separately or in combinations to achieve the desired results. The systems include radiosondes, rawinsondes, meteorological balloons, and instrumented aircraft.

) A sonde is a device used to measure various physical or meteorological parameters as a function of height above the earth's surface, usually for atmospheric probes to heights of 150 km compared to heights of 1 to 3 km of interest to aircraft flyover testing. Sondes are usually carried aloft by a free balloon filled with enough helium to lift the mass of the instruments. The balloon rises to a height where expansion causes the balloon to burst. The instrument package then either falls or is parachuted to the ground where it is recovered, if it can be tracked, or is lost, or destroyed.

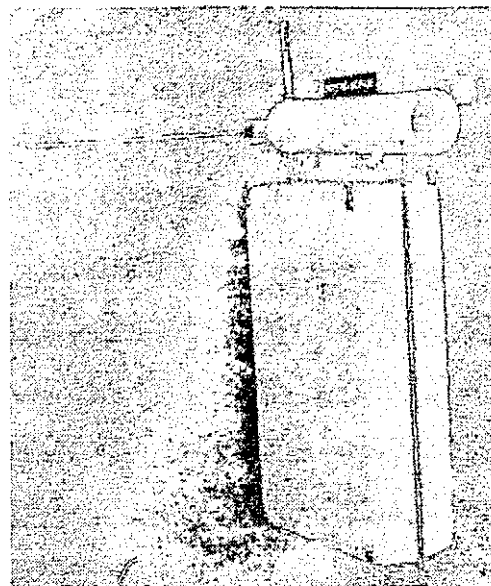
A radiosonde is a sonde equipped with a radio transmitter and instruments to measure air pressure, air temperature, and relative humidity. A rawinsonde is a radiosonde that is tracked by a radio direction-finding device so that wind speed and wind direction aloft may also be determined. Special radiosondes are also available that carry instruments to measure directly wind speed and wind direction and therefore do not require a radio direction-finding device.

) Free-rising radiosondes or rawinsondes are not recommended for testing of aircraft flyover noise. Radiosondes usually rely on some form of natural aspiration for the temperature and humidity sensors, rather than incorporating the weight and complexity of a battery-powered fan. The use of natural aspiration is acceptable for upper-atmosphere probing but can cause problems in the lower atmosphere where there may be large temperature and humidity gradients. The relatively rapid ascension rate of the radiosonde or rawinsonde also makes it difficult to obtain long-term average values for height profiles of temperature, humidity, wind speed, and wind direction. Finally, the initial cost of the tracking/recording system is high and many of the radiosonde/rawinsonde instrument packages will probably not be recovered, thus further increasing test costs.

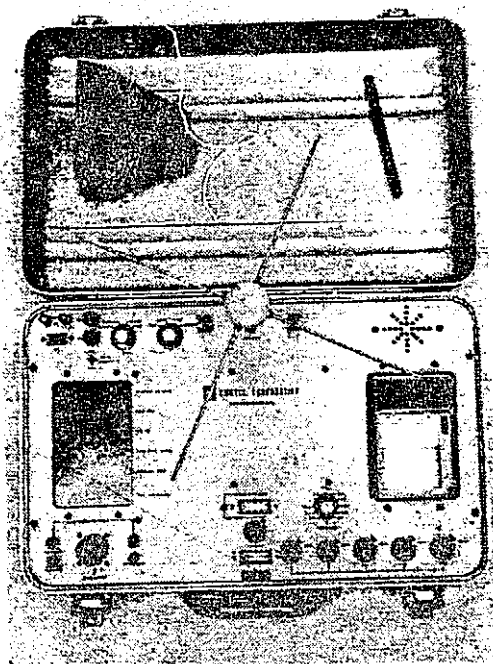
) Tethered radiosonde systems are available that can be used to probe the atmosphere near the microphones, assuming permission can be obtained from the airport's air traffic controller and the airport proprietor to operate such a system. The tethered system uses an aerodynamically shaped balloon, an instrument package with a telemetry transmitter, a receiver and data recorder, and a battery-powered winch. Figure 12 shows typical components.



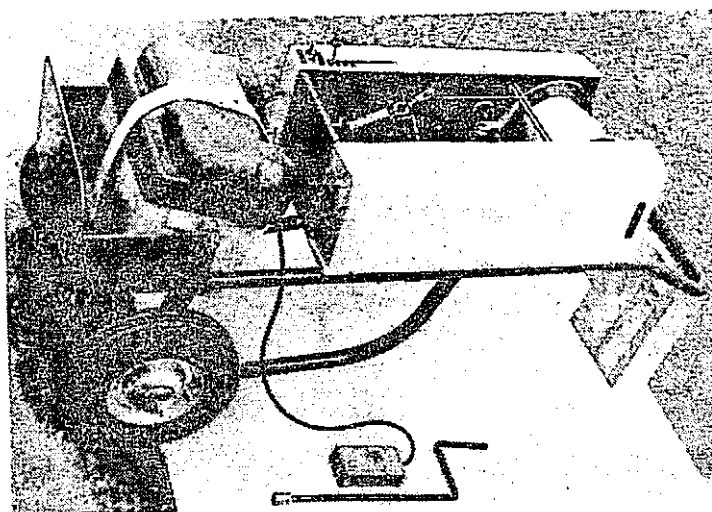
(a) Aerodynamically shaped balloon



(b) Instrument package and telemetry transmitter



(c) Telemetry receiver and strip chart recorder



(d) Battery-powered winch and tether line

Figure 12. -Components of a tethered radiosonde system.

The height to which the instruments will rise is governed by the mass of the instrument package and the tether line. For example, a balloon with a volume of 3.2 m^3 (a length of 4.9 m and a maximum diameter of 1.4 m) will provide enough lift to carry a 1-kg instrument package to a height of 1000 m using 3-mm braided nylon cord. (Lighter and stronger cords made from organic fibers are available at increased cost. Larger balloons are also available to provide more lift, but with higher initial cost and a requirement for more helium.)

The balloon will rise almost vertically in light winds. Indeed, the lift provided by the wind is necessary to achieve a reasonable ascension rate. Ascents, however, should not be attempted if the surface wind speed exceeds $10 \text{ m} \cdot \text{s}^{-1}$ because of the danger of losing the balloon and the relatively expensive instrument package. The descent rate is governed by the torque available from the winch motor and the speed of the motor. Typical ascent and descent rates are between 50 and $100 \text{ m} \cdot \text{min}^{-1}$, meaning that two ascent/descent probes can be made per hour for a height of 1000 m.

The instruments that are carried aloft consist of a thermistor to sense ambient temperature, a carbon-film hygistor to sense relative humidity, a heated thermistor (anemometer) to sense the horizontal component of wind speed, a magnetic compass and potentiometer for wind direction, and a strain gage to sense changes in atmospheric pressure. The wind direction indicator relies on the fact that the aerodynamically shaped balloon always points into the wind. The instrument package is supported below the balloon in a trapeze-like sling to prevent rotation and to maintain a fixed orientation with respect to the axis of the balloon. The heading of the balloon is then determined by calibrating the potentiometer that surrounds the magnetic compass (which is free to rotate and always points to magnetic north) with respect to the body of the instrument package and hence to the axis of the balloon. As the balloon turns into the wind about the tether line, the potentiometer turns about the compass; the voltage across the potentiometer is proportional to the heading.

The outputs from the five sensors are multiplexed and telemetered to a battery-powered receiver on the ground. The receiver records the outputs of the five channels of data in multiplex format as time-gated continuous

sequences of analog information on a strip-chart recorder. A switch-selectable display is also available on a meter for monitoring by the operator as the balloon ascends or descends.

The thermistor and the hygistor are shielded from direct solar heating and aspirated by a small fan to provide a continuous flow of ambient air over the sensing elements and to reduce the response time to sharp gradients in temperature and humidity. The ventilation flow rate should be on the order of $5 \text{ m} \cdot \text{s}^{-1}$.

Instrument accuracies should be no worse than $\pm 0.2^\circ \text{C}$ for temperature, ± 5 percentage points for relative humidity, $\pm 0.2 \text{ m} \cdot \text{s}^{-1}$ for wind speed, $\pm 5^\circ$ for wind direction, and $\pm 16 \text{ m}$ for height (atmospheric pressure).

All instruments should be powered by rechargeable batteries. Spare fully charged batteries should be available to assure enough capacity for a full day of operation. Standard C-cell nickel-cadmium batteries have enough capacity for only about 2 h of operation on warm days, less on cold days. There is a significant current drain to operate the heated thermistor/anemometer and the strain gage/altimeter. It is also advisable to have a spare balloon and an adequate supply of helium. If the tests continue for several days, some provisions should be made for storing (and transporting) the fully inflated balloon in order to save the time and cost of deflating and reinflating the balloon on a daily basis. A spare battery and a battery charger should be available for the 12 V wet-cell battery that powers the winch motor.

Free-rising meteorological balloons can also be used for measuring winds aloft. A balloon is filled with helium and then released. The azimuth and elevation angles of the balloon are tracked with a theodolite and coordinates are noted at fixed intervals of time, say every 30 s. Two theodolites are sometimes used. The ascent rate of the free balloon is a function of balloon diameter, larger balloons having more lift rise more rapidly than smaller balloons. The smallest balloons available have an ascension rate on the order of $200 \text{ m} \cdot \text{min}^{-1}$ and a diameter (just before they burst at a height of about 20 km) on the order of 1 m. The larger balloons may be more readily visible to the theodolite operator, but have ascension rates on the order of 350 to $400 \text{ m} \cdot \text{min}^{-1}$. With tracking data available about every 30 s, the higher

ascent rates of the larger balloons do not provide sufficient details for wind profiles in the height region of interest.

Meteorological balloons for obtaining wind data are known as pilot balloons or pibals. Pibals have been used for many years by the National Weather Service and other meteorologists to determine winds aloft. The balloon is assumed to rise at a constant rate. Wind speed and wind direction are calculated from the ascension rate and the periodic measurements of azimuth and elevation angles. Accuracy and reliability of the pibal method are reasonable and probably adequate for guidance on whether or not the winds aloft are too high for flyover noise testing. Minimum measurement accuracies are on the order of $\pm 1.5 \text{ m} \cdot \text{s}^{-1}$ for wind speed and $\pm 10^\circ$ for wind direction.

Two types of instrumented aircraft are available for measuring meteorological conditions aloft, a radio-controlled (RC) model airplane and a light general-aviation airplane, both propeller-powered. The RC model airplane costs about the same as the tethered radiosonde/balloon system but can be flown to greater heights. The model typically is a high-wing design with a wing span of about 2 m. The operator of the RC model airplane must be careful not to lose sight of the airplane or the airplane could get out of range of the transmitter and fly away until it ran out of fuel, in which case the airplane and the instrument package would probably be destroyed or lost.

Wind data are not available unless some special arrangements are made to track the airplane. The model airplane usually only carries instruments to measure temperature, relative humidity, and height (atmospheric pressure). The exhaust from the engine must be directed away from the instrument package that is mounted on the bottom of the fuselage so that exhaust heat is not sensed by the thermistor and any exhaust water vapor is not sensed by the hygristor.

The two main difficulties with the use of an instrumented RC airplane are cost and operations. The airplane must be tracked visually by an operator. Special care and training are required to be able to safely take off and land the airplane; to fly it over the desired flight path within the region of the atmosphere containing the sound paths; and to operate it properly in the presence of various headwinds, crosswinds, tailwinds, and

wind gradients that are likely to be encountered. With these considerations, the tethered balloon/radiosonde system is preferred over the instrumented RC model airplane.

An instrumented, light, single-engine general-aviation airplane, however, can provide several advantages over a tethered balloon/radiosonde. The costs of developing, calibrating, and maintaining the airplane would usually be borne by a firm specializing in meteorological measurements or a government agency. The flyover noise measurement program would only pay for acquisition and reporting of the weather data. Commercial firms have developed such airplanes and their services or those of a meteorological consultant can be obtained. The Federal Aviation Administration has also developed an instrumented light airplane for meteorological measurements. Reference 49 describes the FAA airborne weather instrumentation system, its evolution and applications.

As with the RC model airplane, it is not customary to attempt to measure winds aloft with a weather airplane, although reliable wind data can be obtained if an inertial navigation system is installed in the airplane. However, unless the inertial navigation system has been previously installed, the increment in cost is probably unjustifiable for flyover noise testing. Wind data of acceptable accuracy can be provided by either the tethered balloon/radiosonde or by tracking of pibals.

The instrumented airplane usually is required only to provide time-correlated measurements of temperature, humidity, and height (atmospheric pressure).

Using the light airplane, a qualitative measure of atmospheric turbulence can be provided for guidance in assessing the turbulent characteristics of the air. The measure of turbulence may have little direct relation to sound propagation although it is useful for judging aircraft handling. If required, instruments can be installed for measuring the rapidly fluctuating components of temperature and velocity induced by atmospheric turbulence, but, as mentioned earlier, measurement of the fluctuating components of temperature and velocity is not recommended until further research is done to establish firm requirements and a corresponding procedure for using the temperature and velocity measurements in subsequent data analyses.

Atmospheric turbulence does, however, affect the stability of the test airplane's speed. Airspeed during a given run not only can fluctuate about a steady mean value, but the mean value can also vary, both types of variations being caused by turbulence.

The temperature sensor on the weather airplane should be installed on a wing away from the heat radiated from the engine and fuselage. A platinum resistance element in a bridge circuit is recommended because it has good accuracy, linearity, and response time. The sensing element should be shielded from solar radiation and installed in such a way as to be insensitive to moisture droplets. A rugged design is required to withstand the vibration environment and the takeoff and landing loads. The resistance of the element varies with the air temperature. The varying dc voltage at the output of the bridge circuit is fed to a signal-conditioning amplifier and then to a strip chart recorder in the airplane. The indicated temperature is a total temperature, but it can also be considered approximately the ambient or static temperature because the weather airplane's Mach number is usually less than 0.15. Commercial systems meeting the above requirements are available for measuring average temperatures in the range required for flyover noise testing (-20° to $+40^{\circ}$ C) with an accuracy of $\pm 0.5^{\circ}$ C.

The recommended system for measuring humidity is one that measures dew point. The humidity then is calculated knowing the air temperature. The preferred system is one that works on the same principle as the system recommended for the surface-tower humidity measurements, namely, changes in the reflectance of light from a stainless-steel mirror that is chilled by a thermoelectric cooler. The sensor should be a rugged, long-life design that can be mounted through the fuselage or a window away from the engine exhaust or one that can be installed in a duct supplying outside air to the cockpit. The mounting surface should be vertical to avoid pressure changes with changes in aircraft pitch angle.

The airborne unit probably will not have the cooling capacity of the ground unit. The dew point depression capability, however, should be at least 36° C for ambient temperatures of 27° C or greater. The reduction in cooling capability for temperatures less than 27° C should still permit determination of relative humidities between 10 and 100 percent for ambient

temperatures between -20° and $+40^{\circ}\text{C}$. For dew points greater than 0°C , the accuracy of the dew point temperature should be no worse than $\pm 0.3^{\circ}\text{C}$. The unit should have a relatively rapid response time for gradients in humidity. A response time of no greater than 2°C per second down to a dew point of 0°C should be adequate. The unit should have built-in balancing and reflectance-standardizing features similar to those for the surface-tower unit. The accuracy of the relative humidity values depends on the accuracy of the temperature and dew point measurements and should be no worse than ± 3 to 4 percentage points over the temperature range of interest. Dew point temperatures should be continuously recorded in flight on an analog strip chart, suitably synchronized with the time of day. Note that, with the recommended system, dew point measurements are independent of airspeed.

Airplane height data are required to determine the profiles of temperature and humidity. Essentially two systems are available: a pitot/static probe for measuring total and static pressures (also used for airspeed) and a radio altimeter.

The pitot/static probe is preferred over the radio altimeter for heights greater than 30 m. A radio altimeter works well if the surface is smooth and flat, and if the airplane is flying approximately level. The maximum usable height is about 600 m where the accuracy is about ± 7 percent. For heights less than 50 m, the accuracy is on the order of ± 1 to ± 2 m.

The pressure signal from the static ports of the pitot/static probe is fed to a pressure transducer. The output of the transducer drives a signal-conditioning amplifier to supply a varying dc voltage to a strip chart recorder. Pressure-lag problems can be minimized by installing the transducer close to the pitot/static probe to minimize the length of the tubing. The signal-conditioning amplifier should be capable of recording heights from ground level to 2000 m. The output range should be adjustable such that the elevation of the runway is always on the strip chart. The accuracy of the height measurements is on the order of ± 5 m for heights greater than 30 m. Below 30 m, ground effects degrade the accuracy of the static pressure measurements and the radio altimeter system is preferred.

Subject to the constraints of existing air traffic, the instrumented weather airplane can be flown on various flight paths to sample upper-atmosphere

weather. Continuous strip-chart recordings should be made of air temperature, dew point temperature, height from the static pressure ports, and height from the radio altimeter. Chart recorders that use electronic direct-print systems (no ink) are preferred.

The airplane should be capable of being flown as low as 5 m above ground level and to a height of at least 2000 m. The airplane should be capable of safe operation at a relatively low airspeed (70 to 80 knots) to accommodate the response time of the instruments to variations in mean values of air temperature and dew point. The airplane should have fuel capacity for at least 4 h of flying. Electrical power to operate the instruments will normally be supplied by onboard rechargeable wet-cell batteries and an inverter for ac power. The power supply for all the instruments should be independent of the aircraft's electrical power supply.

In summary, the recommended systems for measuring upper-atmosphere weather parameters include:

- an instrumented, light general-aviation airplane to measure air temperature, dew point, and height in a region of the atmosphere encompassing sound propagation paths from the beginning to the end of the flyover noise recordings for each test;
- a tethered radiosonde that is carried aloft by an aerodynamically shaped balloon and that can telemeter multiplexed signals for measurement of air temperature, relative humidity, wind speed, wind direction, and height; and
- free-rising meteorological balloons that are tracked by a theodolite to measure wind speed and wind direction as a function of height.

Note that there is an intentional overlap in the recommended systems. There will probably be only one tethered radiosonde and it will be located somewhere to the side of the runway to avoid the flight path of the test airplane and yet be relatively close to the microphones. The instruments on the weather airplane are more accurate than those on the tethered radiosonde and they provide information on both horizontal as well as vertical values of the

meteorological parameters that the tethered radiosonde cannot provide, although the horizontal gradients in temperature and humidity should be small. The accuracy of the wind data from the meteorological balloons is not as good as that from the instruments on the tethered radiosonde, but the information from the pibals provides a relatively low-cost backup measurement as well as data to fill the gaps between the readings from the ascents and descents of the tethered radiosonde. Thus, the primary system for temperature and humidity profiles is the instrumented airplane with the tethered radiosonde for backup. The primary system for wind is the tethered radiosonde with the pibals for backup.

Time Synchronization

Time is the parameter that correlates the four measurement systems: acoustic, tracking, airplane/engine, and weather. The data that are recorded on magnetic tape (acoustic, tracking, and airplane/engine) must be correlated using an IRIG-B digital time-code system from a time-code generator. The four weather-measuring systems (surface, weather airplane, tethered radiosonde, and pibals) should be correlated with reasonably accurate time-of-day event marks from a clock reference.

The time code in hours, minutes, and seconds should be displayed on a digital readout and should be available as binary coded decimal voltages at the output of the time-code generator. The time base for the code should be a temperature-compensated, crystal-controlled oscillator with a stability of no worse than ± 1 part in 10^5 for temperatures between 0° and 60°C . The pulse-amplitude-modulated code should be generated on a precise 1-kHz carrier frequency. Resolution of the output time should be ± 0.001 s. Drift should not exceed 20 ms in 5 h after 2 h for warmup. The option of a coded identification number as well as hours, minutes, and seconds in the output of the time-code generator is recommended for labeling purposes. (If needed for more precise time correlation, an IRIG-A time code based on a 10-kHz carrier frequency is available to give hours, minutes, seconds, and tenths of a second.)

Communication

Two crucial items for the success of the tests are careful pretest planning and good spoken communications. Communications are required to coordinate the field activities and synchronize data acquisition. Combinations of very high frequency (VHF) and FM transceivers are needed depending on range requirements, air and ground control at the airport, and the need for information.

Experience has shown that it is highly desirable to have a clearly designated, centrally located person on the ground who is the test director. The test director is in charge of test operations and is responsible for coordinating the various test activities as the test proceeds. He also conducts the daily preflight and postflight meetings.

During the test, the test director communicates with the test airplane and the weather airplane using two-way VHF transceivers. The frequency of the transceivers should be one that is specially licensed for flight testing, i. e., for ground-to-air and air-to-ground transmissions. The test director should also have receivers to monitor transmissions from airport ground control and air traffic control.

Activities of the ground personnel (acoustic data recording, laser tracker, tethered radiosonde operator, pibal operator, and other personnel who may be involved in the test operations) are coordinated by the test director using two-way FM transceivers. The frequency used for the FM transceivers should be a specially licensed test frequency assigned for business operations on the ground, i. e., for ground-to-ground transmissions only. (Citizens band radios are not recommended because the channels are too crowded.)

The multiple communication functions of the test director make it desirable to provide a separate vehicle (e. g., a van or trailer) as the central station for communications and test operations. The central station would also serve as a place to collect and review daily data logs and records and to perform preliminary data analyses.

Another separate two-way FM ground-to-ground system should be available for the acoustic data van to communicate with an assistant when the acoustic measurement system is being set up, calibrated, and taken down.

All the communication systems not in vans should be portable and battery-powered. The systems in the vans can be powered by 115-Vac, 60-Hz power since the vans are equipped with ac generators. Standard commercial communication systems that can satisfy the requirements are available. The main considerations are adequate output power (adequate range) and intelligibility. The loudspeakers on the receiver should be driven by an adequate amplifier such that the transmissions can be heard and understood a short distance away in the presence of moderate ambient noise.

RECOMMENDED DATA-ACQUISITION PROCEDURES

This section describes procedures for the acquisition of acoustical, airplane, engine, tracking, and meteorological data. We begin by describing the information to be recorded.

Information to be Recorded

A relatively large amount of information is to be recorded. Table 2 lists the acoustical, tracking, airplane, and engine data that, except for the calibrations, are to be recorded for each pass of the test airplane for each flyover noise recording. The acoustical calibrations are recorded twice a day, or more often if a system component is changed. Tracking calibration needs to be done only once per test setup. Special engine parameters that might need to be recorded include various internal engine pressures and temperatures as well as the position of various movable components such as inlet blow-in doors, fan blades, stator vanes, and variable area exhaust nozzles. Table 3 lists the weather data that are to be recorded periodically. Table 4 lists supplemental information that is required for labeling and reporting.

Recording of the parameters listed in table 2 is to be correlated by simultaneous recording of synchronized IRIG-B time code signals. Each of the primary data systems will have a time code generator and a receiver to "set the clock" by synchronizing to a time mark signal broadcast by the National Bureau of Standards over radio station WWV from Washington, DC and Boulder, Colorado. Moreover, to further reduce synchronization error,

TABLE 2. - ACOUSTICAL, TRACKING, AIRPLANE, AND ENGINE DATA

Acoustical data	Tracking data	Airplane and engine data	
IRIG-B time code	IRIG-B time code	IRIG-B time code	
Acoustic pressure	Range	<u>Airplane</u>	<u>Each Engine</u>
Reference tape speed signal	Azimuth	Indicated airspeed	Inlet total pressure
Gain settings	Elevation	Ambient air pressure	Primary nozzle total pressure
Comments and annotations		Ambient air temperature	
Calibration	Calibration	Altitude above mean sea level	Engine pressure ratio (if applicable)
Reference level		Operating gross weight	Shaft rotation speed (each shaft)
Pink noise voltage		Attitude: pitch, roll, yaw	Primary nozzle total temperature
Background noise		Flap deflection angle	Fuel flow rate
		Leading edge device: extended/retracted	Special parameters as required
		Landing gear: extended/retracted	
		Air conditioning: on (no. of units)/off	
		Speed brakes (if any): extended/retracted	
		Angle of attack (if available)	
		Climb gradient or rate of descent	

TABLE 3. — WEATHER DATA

Barograph station	Weather tower	Weather airplane	Tethered radiosonde	Meteorological balloons
Time of day	Time of day	Time of day	Time of day	Time of day
Air pressure	Air temperature	Air temperature	Air temperature	Wind speed
	Dew point temperature	Dew point temperature	Relative humidity	Wind direction
(Continuous)	Wind speed	Height	Wind speed	
	Wind direction		Wind direction	
			Height	
	(Continuous)	(Each profile)	(Each ascent and each descent)	(Each ascent)

TABLE 4. - SUPPLEMENTAL INFORMATION

- Coordinates of each microphone location
- Plan view of test site showing runway and locations of microphones, acoustic data van, tracking van, weather tower, tethered radiosonde, meteorological balloons
- Elevation and slope of runway
- Description of terrain around each microphone location and weather tower
- Block diagrams of instruments used for acoustical, tracking, and weather data with instrument model and serial numbers
- Test airplane registry number, model number, and name-plate information
- Model and thrust rating of test airplane's engines
- Description of the acoustical features of the test airplane's engines: nacelle duct linings, jet noise suppressor nozzle, etc.
- Dimensioned 3-view drawing of the test airplane
- Description of the weather airplane
- Black and white photographs
 - Test airplane on the ground (several views)
 - Test airplane's engines and nacelles (several views)
 - Microphone installations
 - Acoustic data van: interior and exterior
 - Weather tower installation
 - Barometric pressure station
 - Tracking van: interior and exterior
 - Weather airplane on ground (several views, including instruments)
 - Tethered radiosonde (several views, including instruments)
 - Meteorological balloons (several views, including instruments)

a crew member in the test airplane, at the beginning of each day's testing, should broadcast a synchronizing signal at the end of a countdown that is simultaneously recorded on all three data recorders. Another synchronizing signal should be broadcast at the conclusion of the day's testing to assess any drift in the time code generators. The accuracy of synchronization among the three stations should be no worse than ± 50 ms.

The four weather systems (or five, counting the surface weather tower and the surface barometric pressure recorder as two separate items with respect to time synchronization) can be adequately correlated with each other and with the acoustic data through a WWV time check obtained at the acoustic data-recording van. Time of day should be noted on the strip-chart records with an event marker or another suitable means. The 24-h clock system is recommended for noting time of day.

The weather data, as indicated in table 3, are to be recorded continuously for surface conditions or at a high sampling rate for the weather aloft. During data processing the meteorological data will be synchronized with the flyover noise recordings by interpolating to the time of day given by the IRIG-B time code for each run.

Acoustical Data

Number and locations of microphones. - The choice of microphone locations depends on test objectives and the flight-testing procedure. As mentioned earlier, it is considered that ANOPO objectives can best be met by a series of nominally level passes over an array of ground microphones. Assuming that the tests are conducted in the vicinity of a long runway or taxiway and that the test site meets the criteria described earlier for openness and flatness, the recommended microphone array is shown in figure 13.

There are 12 microphone stations in figure 13, using up 12 of the 14 tracks on the acoustic data recorder. Five of the 12 stations are on the runway. The best location for the runway microphones is along the runway centerline, assuming the runway is not an active one. If the only available runway (or taxiway) is active, then the microphones would be placed to one side of the runway.

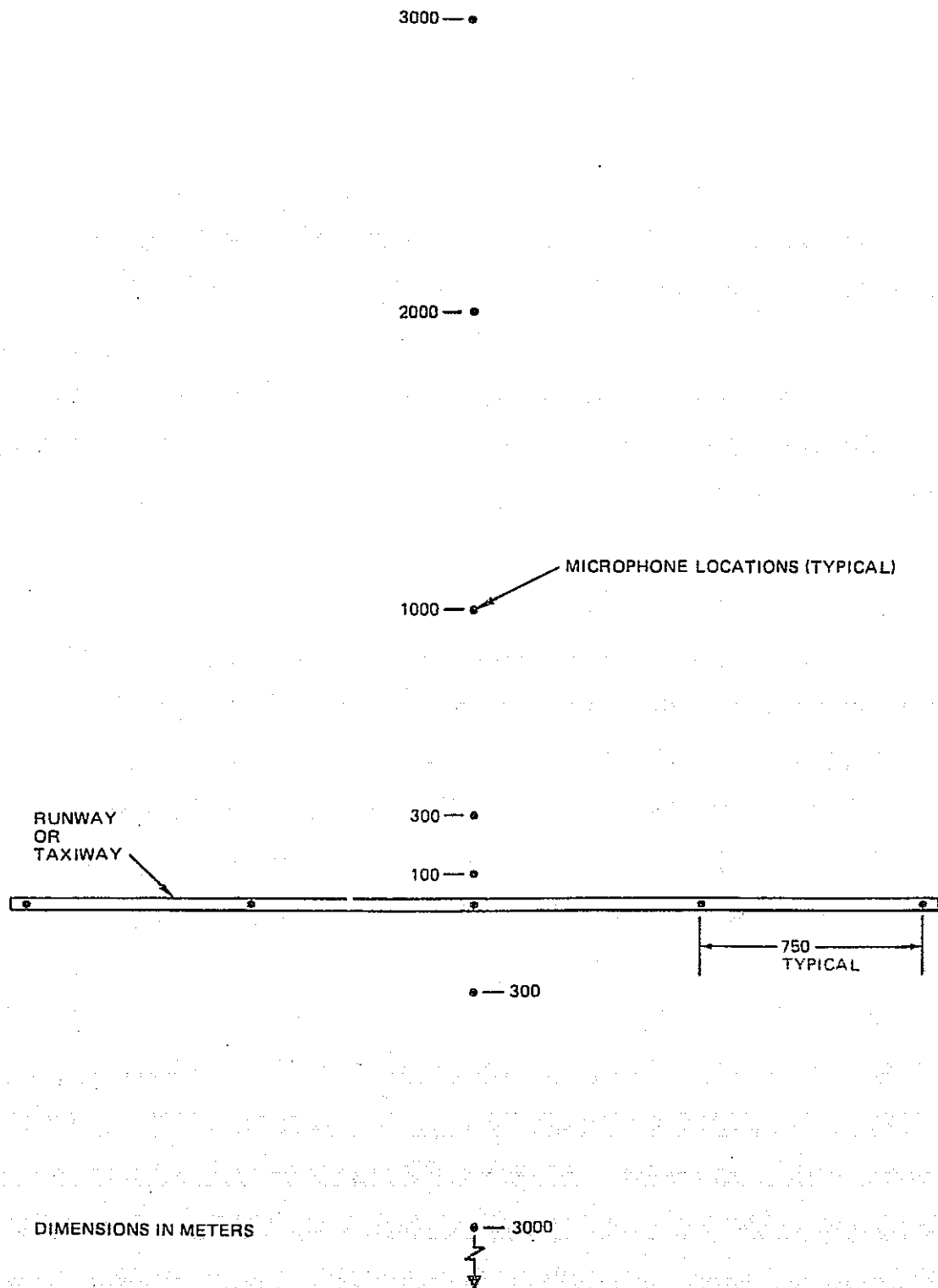


Figure 13. -Microphone locations (plan view).

The intent of spacing a number of microphones under the flight path is to make use of the time and ensemble averaging method described in reference 46 to improve the resolution of airplane position as well as the correlation of airplane position, at an instant of time, with the corresponding sound pressure levels, i. e., an improvement in the resolution of the noise emission angle θ . Since finite sampling times are required to establish reasonable values of statistical confidence for the random aircraft noise signals (particularly for the low-frequency 1/3-octave bands), since the airplane is continuously moving, and since the amplitude of the mean-square sound pressure in any 1/3-octave band is also continuously changing with time (the airplane being a directional noise source), there will be inherent errors associated with attempting to relate a time-averaged sound pressure level with a corresponding aircraft position and sound-emission angle. The errors can be reduced by ensemble averaging several sets of nominally identical and independent flyover noise signals that have previously been time averaged.

In order to appreciate the potential for angular position error, consider the geometrical relationships shown in figure 14. The angle ψ indicates the

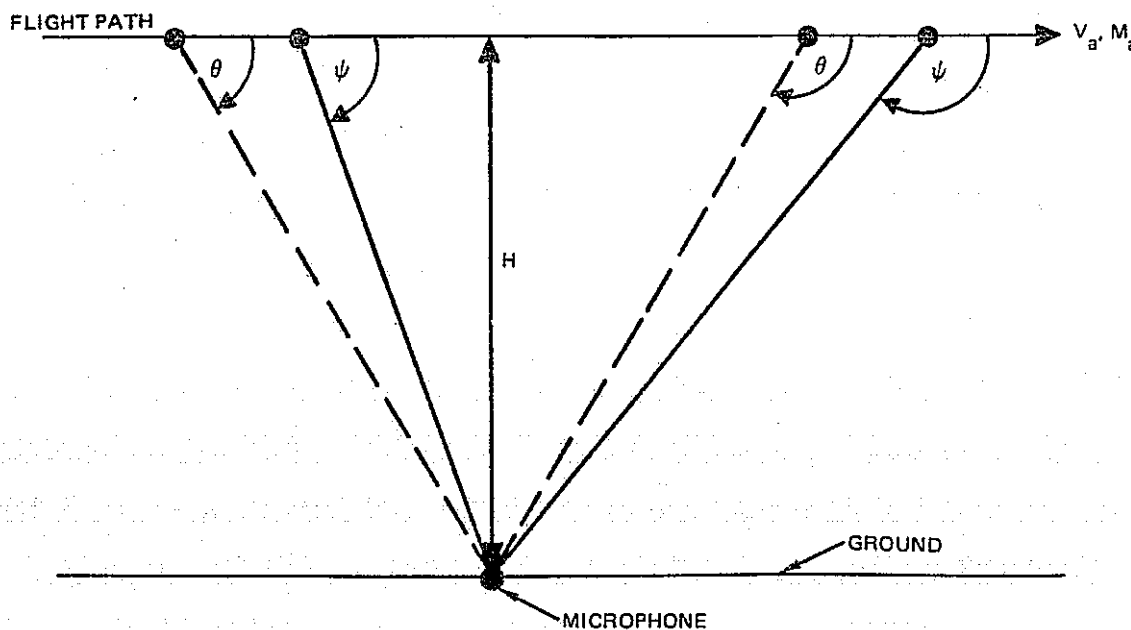


Figure 14. -Geometrical relationships for relating sound emission angle to sound reception time at the microphone.

position of the airplane on a level flight path at the time when the sound is received at the microphone. The angle θ indicates the position of the airplane when the sound was emitted. The airplane is considered to be a point source of sound moving with uniform velocity V_a (or Mach number $M_a = V_a/c$ where c is the speed of sound in the constant-temperature ambient air). The flight path is at a height H above the microphone. (Item 7 in Appendix A discusses some of the problems that arise when determining locations for equivalent acoustic point sources for an actual aircraft.)

The sound reception time t is assumed to be zero when the airplane is directly overhead (i. e., when $\psi = 90^\circ$ and $\theta = \cos^{-1} M_a$). The time t is negative for $\psi < 90^\circ$ and positive for $\psi > 90^\circ$. Note that angles are measured from the nose of the airplane.

For the geometry in figure 14, the relation between airplane position angle and sound emission angle is given by

$$\begin{aligned}\tan \psi &= \sin \theta / (\cos \theta - M_a) \\ &= (\cot \theta - M_a \csc \theta)^{-1}.\end{aligned}\tag{5}$$

The sound reception time at the microphone is related to the sound-emission angle by

$$t = (H/V_a) (M_a \csc \theta - \cot \theta).\tag{6}$$

The longest time interval for the duration of a single flyover noise signal will be for a run at the highest height and slowest airspeed.

If the ambient noise levels permit data to be obtained for sound-emission angles between 20° and 160° , then use of equation 6 shows the duration to be about 55 s for $H = 1000$ m, $V_a = 100$ m·s⁻¹, and $c = 343$ m·s⁻¹. Thus each microphone in the line should be spaced 5500 m apart in order for the signals to be independent for an angular range of $20^\circ \leq \theta \leq 160^\circ$.

A spacing of 5500 m is impractical since there should be four or five microphones in the array to yield a meaningful ensemble average. The 750 m spacing in figure 13 for the five runway microphones represents a compromise in terms of the heights, airspeeds, and angular ranges for which inde-

pendent samples can be guaranteed. Note that if $H = 100$ m and $V_a = 70$ m·s⁻¹, the duration would be only about 8 s for $20^\circ \leq \theta \leq 160^\circ$ and the spacing would need to be 560 m. Thus, the 750 m spacing will provide many opportunities to employ the ensemble averaging procedure to improve the quality of the data.

The greatest advantage of the ensemble averaging technique in reducing the uncertainty in aircraft position occurs during the portion of the flyover noise signal when the angular rate of change is largest. For low height runs, the rate of change of aircraft position with time can be very rapid. From figure 14, the airplane position angle can be expressed as

$$\tan \psi = -H/(V_a t). \quad (7)$$

The rate of change of angle is then

$$d\psi/dt = (H/V_a) / \left[(H/V_a)^2 + t^2 \right] \quad (8)$$

in radians per second. The rate of change is greatest when $t = 0$ or around the overhead position.

Again for $H = 100$ m and $V_a = 70$ m·s⁻¹ at $t = 0$, the rate of change becomes

$$\begin{aligned} d\psi/dt &= 0.7 \text{ rad} \cdot \text{s}^{-1} \\ &= 40 \text{ deg} \cdot \text{s}^{-1}. \end{aligned} \quad (9)$$

The $40 \text{ deg} \cdot \text{s}^{-1}$ rate of angular change represents uncertainty of $\pm 20 \text{ deg} \cdot \text{s}^{-1}$ in the determination of airplane position in this example for a single microphone measurement. As shown in reference 46, the uncertainty can be reduced in direct proportion to the number of microphones used in the ensemble average. Thus, with five microphones, the uncertainty is reduced from $\pm 20^\circ$ to $\pm 4^\circ$ at the overhead position.

We note that one important requirement with the use of a linear microphone array and ensemble averaging is that the airplane must have reached a stabilized flight condition (airspeed, attitude, and power setting) well before reaching the first microphone and must maintain the condition until well past the last microphone. This requirement is needed to ensure that all microphones sample the same flyover noise signal.

Thus, the line of runway microphones should provide a good definition of the time variation of the sound pressure levels in each 1/3-octave band over a wide range of angles. Variations in height, engine power setting, and airspeed will be obtained by making a number of different passes. The quality of the data will also be improved by obtaining several repeat runs.

Five microphones in figure 13 are shown spaced out along a line normal to the flight track. The side microphones provide data at longer distances and on propagation effects at shallow angles to the surface, and can, if a test objective, provide data on the location of noise level contour lines. Non-symmetrical noise fields caused by crosswind components can also be studied. Examples of the ranges in elevation angles and slant distances (at the time of closest approach) are shown in table 5.

TABLE 5. - ELEVATION ANGLES AND MINIMUM SLANT DISTANCES FOR MICROPHONES TO SIDE OF FLIGHT TRACK

Distance to side, m	Elevation angle, deg	Minimum slant distance, m
(a) 100 m height		
100	45	141
300	18.4	316
1000	5.7	1005
2000	2.9	2003
3000	1.9	3002
(b) 1000 m height		
100	84.3	1005
300	73.3	1044
1000	45	1414
2000	26.6	2236
3000	18.4	3162

The two microphones on the other side of the runway are intended to provide data to check the symmetry of the noise source and the noise propagation. Past experience has indicated that the noise field of some airplanes is not symmetric. Propagation effects also may not be symmetric due to temperature gradients, winds, and differences in the terrain.

The combination of runway microphones, side microphones, several passes at various heights and engine power settings, and analytical extrapolation techniques should be able to yield valid curves of noise level versus distance at time of closest approach, as a function of engine power setting. The combination will also provide the capability of obtaining data to verify noise-prediction methods and to study the effects of forward motion on noise generation.

Note also that calculation of distances between the aircraft reference point and the microphones requires knowing the coordinates of the location of the microphones and the laser tracker relative to some fixed benchmark on the ground as well as the location of the plane of the runway and the runway centerline relative to the benchmark. The x coordinate is taken along the extended centerline of the runway. Lateral deviation and height above ground are given by the y and z coordinates, respectively. If line of sight permits, the x, y, and z coordinates of the locations of the microphones and surface weather measurements can also be determined by the laser tracking system, thereby eliminating the requirement for surveying these locations.

Microphone system. - In this section we discuss four aspects of the microphone system: height above the surface, microphone orientation, the use of windscreens, and the installation of microphones on the towers.

Height above surface: The microphones should be as far above the surface as possible to obtain the best measure of the free-field spectrum shape and avoid spectral irregularities caused by ground reflections. Because of the requirement that the microphone system be transportable and the requirement for periodic microphone calibrations during a test, it is probably not practical to consider microphone heights greater than 10 m. The recommended microphone support is the hinged tower arrangement shown in figures 7 and 8 with optional guy wires or outriggers.

The standard height for measuring weather parameters around an airport is 10 m, and that height is recommended for the surface weather measurements for ANOPO flyover noise tests. To be consistent with the surface weather measurements and the needs for transportability, erection, and lowering, a 10-m height is also recommended for the microphones. Microphone height means the distance between the ground surface and the center of the microphone diaphragm.

There is no single criterion that can be given for how high the microphone should be in order to avoid spectral irregularities caused by ground reflection effects. The height needed is a function of the lowest frequency of interest (say 45 Hz as the cutoff frequency for the 50-Hz band), the impedance (phase change) of the reflecting surface, and the angle of incidence of the sound wave onto the reflecting surface.

Some guidance, however, can be obtained from the analytical studies that are available. Reference 50, for example, indicates that for an acoustically perfect reflecting surface, the spectral irregularities in the difference between the sound pressure measured with and without a reflecting plane present become relatively minor when the value of the parameter $\Delta r/\lambda$ is between 2 and 3, say 2.5. The numerator Δr is the difference between the reflected path length and the direct path length and λ is the wavelength of the sinusoidal sound signal.

When the sound-emission angle is 90° , $\Delta r = 2h$ where h is the microphone height. Then, using $c = f\lambda$ where c is the speed of sound and f is frequency, we have

$$\Delta r/\lambda = f\Delta r/c = 2.5 \quad (10)$$

or

$$f = 2.5c/\Delta r = 2.5c/2h = 1.25 c/h. \quad (11)$$

For $h = 10$ m and $c = 343 \text{ m} \cdot \text{s}^{-1}$, equation 11 indicates that, for the case when the airplane flies over a microphone above an acoustically perfect reflector, most of the ground reflection effects are below 43 Hz. For angles of incidence other than 90° and for reflecting surfaces having a finite acoustic impedance, there will still be some spectral irregularities in the spectrum above 45 Hz. The magnitude of the irregularities, however, should not be

more than ± 3 dB and should be confined to the bands with center frequencies of 50, 63, 80, and 100 Hz. For bands above 160 Hz, the resulting spectrum should be free of spectral irregularities and, theoretically, should be 3 dB above what would have been measured in a free field. If spectral irregularities are noted in the four bands from 50 to 100 Hz, it should be feasible to define an algorithm to use in a computer program for smoothing the irregularities. (See item 4 of Appendix A.)

Orientation: The orientation of the microphone with respect to the flight path requires careful consideration. There is a single preferred orientation for all microphones and that is with the diaphragm in the plane defined by the flight path and center of the diaphragm. This orientation provides grazing or 90-degree incidence for all times throughout the duration of the recording. The advantage of this arrangement is that the microphone and windscreen response corrections become independent of time thereby greatly simplifying the determination of frequency response corrections during data processing.

Thus for the microphones along the runway under the nominal flight path, the choice is clear. These microphones should be installed on the boom of the tower in figure 7 so that the axis of the microphone is parallel to the ground and perpendicular to the runway centerline and with the diaphragm end of the microphone pointing out away from the tower.

Grazing incidence should also be used for all microphones to the side of the flight path. To achieve grazing incidence for microphones at different distances from the runway centerline and to accommodate different heights for the test flight paths, however, requires that a theoretical orientation angle (relative to the vertical) be calculated in advance for each microphone. Each microphone must also be equipped with a small leveling device (e.g., a bubble level) and an orientation angle indicator. Prior to each series of runs at a given flight path height, each of the side microphones must be set to the appropriate orientation angle. During data processing, the assumption will be made that the incidence was at 90° throughout the recording unless the actual airplane height was significantly different than the target height.

Windscreen: The recommended windscreen should always be installed regardless of the wind speed. The reason is for convenience and to ensure that the data processing never has to make a choice with respect to wind-screen installation.

Microphone towers: The first step in erecting the microphone towers would be to locate the sites by surveying or by using the laser tracker from the aircraft space-positioning system. If the towers are to be braced with guy wires (as indicated in figure 7), then the procedure described in Appendix B may be followed. If no guy wires are required, the footing board and sole plate can be simply pegged to the ground, the tower attached, the boom and microphone attached, and the tower raised. Outriggers or some other suitable bracing should be used to keep the tower vertical.

Recording system. - Once the tape recorder has been set up as described above in the discussion of tape recorder performance requirements and the maximum and standard input-voltage record levels have been established, the remaining considerations are the gain settings to be used during recording, how to determine the duration of the recordings, and the recording mode to be used.

Gain: The reference level calibration establishes the voltage at the input to the signal conditioning amplifier, for each channel, that corresponds to 124 dB at the microphone (assuming a pistonphone or comparable calibrator producing that level is used to establish the reference sound level). The reference acoustic pressure is recorded, along with the IRIG-B time code, on each data channel at an input voltage corresponding approximately to the standard record level by appropriate adjustment of the 5-dB step attenuators in the signal-conditioning amplifier. The tape recorder operator notes the gain (attenuator) setting for each channel that yields the standard input-voltage recording level for 124 dB at the microphone. Recall that the standard record level is 10 dB below the maximum record level to allow for random peaks in the flyover noise signal. Voice annotations and time code signals can be recorded on edge tracks instead of two of the 14 data tracks.

To record airplane noise signals requires an estimate, for each of the 12 microphones for each scheduled test run, of the maximum overall sound pressure level (20 to 20 000 Hz bandwidth) that the airplane will generate.

The operator then adjusts the gain (or attenuator) setting for each channel by the difference between 124 dB and the predicted maximum overall sound pressure level. This requirement means that estimates of the maximum overall level must be available in advance of the tests. Alternatively, the airplane could fly various practice runs at different power settings to provide information on the amount of gain required for each data channel. Flying several practice runs, however, is time consuming and expensive and may mean that favorable weather conditions are lost.

The desire here is to record the maximum value of the flyover noise signal as close as possible each time to the standard record level. The reason for this requirement is the limited signal-to-noise ratio (limited dynamic range) of the tape recorder. If the tape recorder has a signal-to-noise ratio of 48 dB and 10 dB is used to allow for the high crest factor of the signal, then it is unlikely that a signal-to-noise ratio of more than 35 dB can be counted on. Thus, if the signal record level is below the standard record level, the effective signal-to-noise ratio will be less than 35 dB and could be 25 to 30 dB. Since as much of the signal as possible in each 1/3 octave band should be recovered, over as wide a range of sound emission angles as possible, it is mandatory that careful attention be paid to the selection of input gain setting. The gain settings used each time for each channel should be annotated on the tape for use in data processing.

The gain settings for the ambient noise recordings must be identical to those used for the corresponding flyover noise recordings. Furthermore, the gain setting must never be changed during any recording (for example, to correct an error). If mistakes in gain setting are made, the test run should be repeated or the data point should be regarded as lost.

Duration of recordings: Specifying in advance a procedure for determining the duration of a recording is not a simple matter, other than saying that the total duration should be compatible with the requirements of the data-processing system including the size of various dimensioned matrices and subprograms in the data processing computer program, and the tabular (or tape file) output formats. Another consideration is economy of tape since much tape could be wasted by starting too early and stopping too late.

First, there must be agreement on a definition of duration. For ANOPO purposes, duration, in any band, is that time interval between when the fly-over noise signal (as recorded) first becomes 5 dB more than the corresponding steady ambient noise and the last time it is 5 dB above the ambient noise level. In the field, the duration is that of the wideband (linear) sound pressure level as indicated on the strip chart recorder used to monitor signals at the input to the tape recorder.

Duration is not that of the top 10 dB or top 20 dB of the signal, nor is it the time between when the airplane is some distance before reaching the first microphone and some distance past the last microphone. Nor is duration the time between when the tape recorder operator first begins to hear the airplane (through a headset monitoring the output of some microphone) and when he can no longer hear the airplane. Visual sightings of the airplane are also not valid methods of determining the recording duration.

The basic intent is to record (at as high a record level as is safe) as much of the signal as possible over as wide a range of sound emission angles as feasible. The recommended procedure for determining recording duration time is as follows.

For each run, the crew of the test airplane establishes stabilized flight conditions (power setting, height, airspeed, attitude, and configuration) at some point well before reaching the end of the runway, say at least 90 s worth of distance or on the order of 4 to 5 km. The flight crew should be advised in advance of the time interval over which they are expected to maintain the conditions and they should be notified of landmarks to the side of the flight path by which to gauge when they should be set up. The landmarks should be off both ends of the runway to permit operations in both directions over the runway. On reaching a stabilized setting at the target test conditions for the particular run, a member of the flight crew broadcasts a countdown and a mark signal. The airplane should maintain the target conditions throughout the duration of the recording. The recording (of acoustic, space positioning, and airplane and engine data) begins at (or slightly before) receipt of the mark signal. The countdown and mark signals should be recorded on the voice track. This method should allow sufficient time to acquire the ambient noise

recording and the buildup of the signal at the first microphone. (For each run, the recording of corresponding ambient noise should immediately precede the flyover noise recording and should be at least 20 s long.)

The time for terminating the recording can be estimated, in advance, for the last microphone on the runway by using equation 6 with a value for θ of 170° , assuming the ambient noise levels are low enough. The operator in the acoustic data van monitors the wideband sound pressure levels from the last microphone under the flight path. When the aircraft noise signal is no longer above the ambient noise, the recording is terminated and a "data off" signal is broadcast. The "data off" signal indicates that the recordings of tracking and airplane/engine data should be terminated and the airplane should break off and go around to another pass. A good communication system is required to assure the success of the method.

With these guidelines, the duration of the recordings will be about 90 s for passes at a height of 100 m and about 180 s for passes at 1000 m, assuming a 3000-m spacing between the first and last microphone and airspeeds between 70 and $100 \text{ m} \cdot \text{s}^{-1}$.

Recording mode: The recommended instrumentation-grade multiple-channel tape recorder will have the capability for recording data signals by various techniques. The techniques will likely include frequency modulation (FM), amplitude modulation or direct, and pulse code modulation (PCM). The PCM mode is used for recording digital, not analog data.

The FM mode should be used to record acoustic data. The instructions of the tape recorder manufacturer should be followed for setting the carrier frequency and adjusting the frequency deviation (see earlier discussion under Instrumentation Performance Requirements). The 50 or 100 kHz tape-speed reference frequency should be recorded in the direct mode on one of the 14 tracks, preferably tracks 6, 7, 8, or 9 near the center of the tape. Voice annotation, comments, and time synchronizing signals transmitted from the test airplane should be recorded on one of the edge tracks and in the FM mode. IRIG intermediate-band electronics and a recording speed of $76.2 \text{ cm} \cdot \text{s}^{-1}$ ($30 \text{ in} \cdot \text{s}^{-1}$) are recommended.

Time code signals should be recorded on the other edge track (or a spare data track) and should be recorded in the direct (not FM) mode. Direct mode recording allows the tape to be searched to find a particular run or a calibration using the fast forward and fast rewind speeds, i. e., at 405 to 610 cm·s⁻¹ (160 to 240 in·s⁻¹). The very high high-frequency response of the direct mode (typically to 400 kHz) will accommodate the five- to eight-fold increase in the frequency of the time-code generator signals and permit the data-processing operator to monitor the timing signal, even though it changes very rapidly. If time code signals were recorded using FM electronics, the tape might have to be searched at the same speed as the record speed, thus considerably increasing data-processing time.

Ambient noise. - Recordings of ambient noise levels (including the contribution of electrical background noise) are required for processing the acoustic pressure signals. The questions are when to record, with what gain setting, and for what duration. The guiding principle here is that a separate specific sample of ambient noise is required for each different test run. It is not sufficient to record one sample (or even two or three samples) and then to consider that sample(s) to be representative of ambient noise levels for all flyover noise recordings.

The reason for requiring separate recordings of ambient noise for each flyover noise recording is, of course, because the ambient noise level is never constant; it always fluctuates. The recommended procedure, as mentioned above, is to record at least 20-s sample, at the gain setting used for recording the flyover noise signal, prior to the initial buildup of the sound from the airplane.

During the flyover noise testing, the values of the linear and A-weighted ambient acoustic noise levels should be monitored periodically on the strip-chart level recorder to ensure that the total ambient levels have not increased for some reason. If the ambient noise levels do increase, then the reason should be ascertained. If it is determined that high ambient acoustic noise levels are going to persist, it may be necessary to terminate the test and reschedule for another day, or relocate the microphones, or move to another test site, or abandon attempts to obtain long-distance or low-engine-power data.

Calibrations. - Field calibration requires three elements: (1) a single-frequency reference-level determination and sensitivity check, (2) a determination system frequency response to pink noise, and (3) a determination of the electrical background noise level. It is not recommended, or considered necessary, to attempt to perform in the field, insert voltage calibrations or frequency-response calibrations by the pressure-response (electrostatic actuator) method. These procedures are part of the supporting efforts to be carried out by a calibration laboratory.

With instrumentation-grade tape recorders using FM recording techniques and instrumentation-grade magnetic recording tape, and with the stability of the components in the acoustical measurement system, there is no need to have calibration signals on each reel of tape used during a day's testing. Unless a change (intentional or unintentional) is made to the acoustical data-acquisition system once it is set up (for example, replacing a microphone or a preamplifier), it should be sufficient to record calibration signals at the beginning and end of each test day. However, if a significant break occurs during the testing for some reason (for example, a two-hour break for refueling), it is recommended that advantage be taken of the opportunity to record another set of calibration signals on each acoustic data channel. Additional reference level calibration, for example, will help in assessing the drift, if any, in the sensitivity of each channel during the day.

Calibrations are required for each test day. It is recommended that the windscreens, microphones, preamplifiers, power supplies, and operational or line-driving amplifiers (and associated batteries) be removed at the end of each test day. The microphone towers, preamplifier extension cables, and signal cables can be left in place until the end of the tests. (The weather tower instruments should also be removed at the end of each test day.) New calibrations are required at the beginning of a test day when the instruments (including fresh or recharged batteries) are reinstalled.

Although specifically not part of the field calibrations it is appropriate to enumerate the laboratory calibration efforts required to support the flyover noise-measurement program. The laboratory tests should include all components of the data-acquisition and data-processing systems (except the preamplifier extension cables and the microphone signal cables) and should be

accomplished in the 60-day period prior to the start of the flyover noise tests. Descriptions of the laboratory calibration efforts are given in Appendix C.

With the above understanding of the role of laboratory calibrations, the recommended procedures for field calibrations are as follows:

Reference level: With the recommended pistonphone, the nominal reference sound pressure level is 124 dB (re 20 μ Pa) at a nominal frequency of 250 Hz. The protective grid cap should be in place over the microphone diaphragm and the reference tone should be recorded for at least 20 s at the standard record level. Experience has shown that it is best to keep the pistonphone in a warm place when it is not being used for actual calibration. Low ambient temperatures have been known to affect the operation of the pistons and hence the output waveshape. Some pretest calibrations may be recorded in the early morning hours in the winter when the ambient temperature could be as low as -10° to -15°C , although problems have been noted at temperatures of 0° to 5°C . The difference between the reference levels at the beginning and end of any test day should not be more than 0.5 dB. If there is opportunity to obtain more than two reference level calibrations on a given test day, the maximum difference between any pair of calibrations should not exceed 0.3 dB.

Frequency response: The system frequency response is defined by recording the output of the pink pseudo-random noise generator thorough the preamplifier into the data-acquisition system. The pink noise signal should be recorded for at least 60 s at the standard record level. The wideband rms voltage at the input to the preamplifier should be on the order of 5 to 10 mV.

Background noise: Install the dummy microphone in place of the actual microphone and record the electrical background noise at the standard record level, or as close to the standard record level as allowed by the maximum available amplifier gain. The sample of electrical background noise should be at least 30 s long. The purpose of the background noise recording is to assess the electrical noise floor of the system.

Airplane and Engine Data

Using the calibrated instruments described in the previous section, record the time-synchronized airplane and engine parameters listed in table 2

on the onboard digital data system. The time synchronization signals should also be recorded. The parameter sampling rate should be at least five samples per second for the duration of each recording between the two timing marks described above for the recording of acoustical data.

Steady operation of the engines and the airplane is normally required throughout each data run. Airplane and engine parameters should be monitored during each run and the run should be repeated if significant deviations from target conditions occur during the run. Variations in airplane attitude and configuration (flap deflection) may be required to minimize the change in airspeed that will occur when trying to maintain level flight and constant engine power setting.

Airplane Space-Positioning Data

Use the calibrated laser tracking system to record the time-synchronized aircraft space positioning information listed in table 2 on a digital tape recorder. The parameter sampling rate should be at least 10 samples per second for the duration of each run between the two timing marks. Timing mark synchronizing signals should also be recorded.

Meteorological Data

Two types of meteorological activities are required to support the fly-over noise measurements: forecasting and acquisition of meteorological data.

Forecasting. - Two levels of weather forecasting support are required in planning and conducting flyover noise tests. One level is that of producing general broad-area synoptic weather forecasts for the near-term and more long range. These general forecasts will indicate trends of weather fronts, winds, and precipitation. The second level of forecasting requires specialized capabilities to predict atmospheric conditions in the specific area around the test site for scheduled test days.

The services of many commercial firms and government agencies can be obtained to provide the general weather forecasts, both on a historical basis and for various future times. The unique requirements of the second level of forecasts, however, will need the services of a meteorological

) specialist. The specialist will be expected to be able to predict if the atmospheric parameters of interest (temperature, humidity, precipitation, wind speed, and wind direction) will satisfy the meteorological test criteria at the surface and aloft in the region of the sound field. Furthermore, the specialist will also be expected to predict if certain special test conditions will or will not be present (for example, certain temperature or humidity profiles). On a given test day, the specialist will also be expected to indicate when unfavorable atmospheric conditions can be expected to become favorable, and vice versa (for example, when will the strong inversion burn off? when will the wind die down or become too strong?).

The person making the specialized weather forecasts should coordinate the predictions with the personnel involved in the weather-aloft measurements at the test site and with the test director.

) Measurements. - The purposes of the meteorological measurements are to monitor atmospheric conditions throughout the test period to ensure that they comply with applicable test criteria (stopping the test and rescheduling, if necessary, if the conditions do not meet the requirements), and to provide records that will be used in subsequent data processing and analysis. The dual purposes apply to both the surface and the weather-aloft measurements.

Meteorological parameters at the surface should be measured at a location near the microphone array. Vertical profiles of conditions aloft should be sampled in the region of the atmosphere through which the sound is propagating to the microphones. Atmospheric pressure can be measured and recorded at a location near or in the central acoustical data-recording van.

The calibrated meteorological instruments described in the previous section should be installed to measure the parameters listed in table 3. The surface measurements at the weather tower and the barograph station should be recorded continuously from at least one hour before the scheduled test start time until the end of the flyover noise testing. Similarly, the measurements of weather aloft (instrumented light airplane, tethered radiosonde, and pibals) should begin at least one hour before the scheduled test start time and continue throughout the day. All measurements must be time correlated as described earlier.

The location of the fixed weather measurement stations should be in or near the array of microphones so that the data may be considered representative of average conditions along the sound path. Figure 15 shows a suggested arrangement for the fixed weather stations as well as the acoustic data van, laser tracking van, the test director's central communication station, and the flight tracks for the weather airplane. The distance between the various fixed stations and the closest microphone should be such that the noise produced by operation of the station does not contribute to the ambient noise level at the microphone.

The terrain around the weather tower should be similar to that around the side microphones. The temperature, humidity, and wind instruments on the weather tower should be approximately 10 m above the local terrain. If the barograph is located outside the acoustic data van (as indicated in figure 15) it should be in an instrument shelter and about 1.5 m above the ground.

The tethered radiosonde should be put up and lowered at least twice per hour. The multiplexed data from the temperature, humidity, wind speed, wind direction, and height probes should be continuously recorded (on time-synchronized chart paper) during each ascent and descent. The total height should be at least 500 m. A height of 1000 m is preferred if it can be obtained at the twice-per-hour rate.

Pibals should be released approximately every 30 min and should be tracked (if visible) to a height of at least 1000 m (for 5 min if the smaller balloons are used). Records should be kept of azimuth and elevation angles and the reading times. Wind-profile data should be calculated in the intervals between releasing balloons so that it can be available to the acoustical test crew for comparison to the established criterion for wind aloft. Azimuth and elevation angles from the theodolite tracking telescope should be read at least every 30 s (approximately every 100 m of height).

The weather airplane should be flown along ascending and descending flight paths near the arrays of runway and side microphones as indicated in figure 15 by the double-ended arrows for the flight tracks. At least two ascents/descents per hour should be made. The time-correlated temperature, humidity, and height data should be recorded continuously throughout each

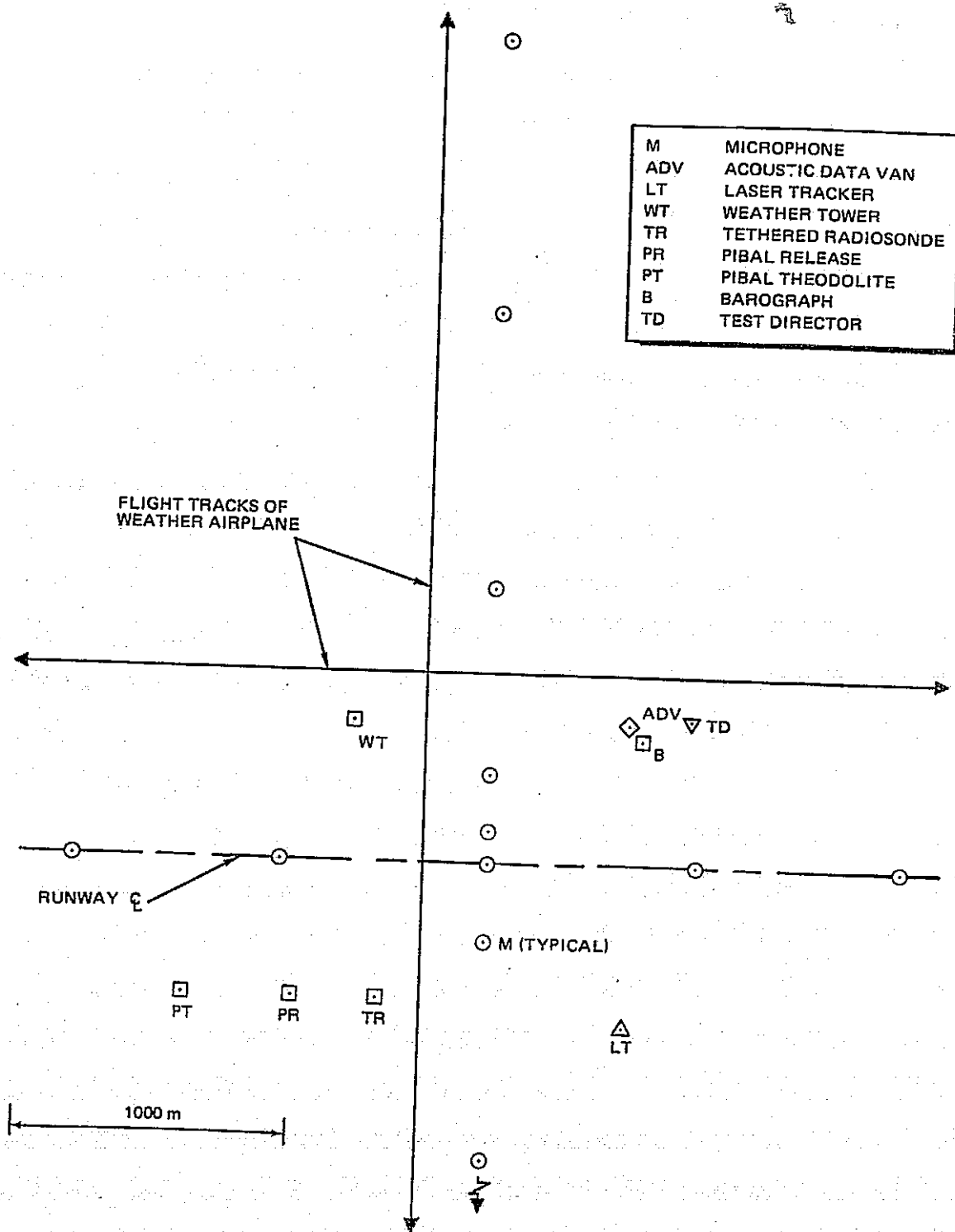


Figure 15. -Locations of acoustic, tracking, and weather measurement systems (plan view).

ascent and descent. The airplane should climb to, and descend from, a height of at least 1000 m or the maximum height of the test airplane. The flight path and flight times should not interfere with the operation of the test airplane. Moreover, the propeller and engine noise produced by the weather airplane should not contribute to the ambient noise level during the recording of the noise from the test airplane. The crew of the weather airplane should note and report any unusual wind or turbulence conditions.

The operation of the chilled-mirror dew-point measuring instruments on the weather tower and in the weather airplane should be checked occasionally throughout the test day to ensure that dust has not collected on the mirror enough to change the reflectance beyond the ability of the instrument to compensate.

Prior to the start of actual recording of flyover noise, the various weather-measuring systems should be set up and checked out. The output of the separate systems should be compared one with another to determine the magnitude of any systematic errors. Comparison should also be made with the meteorological measurements provided by a permanent meteorological facility in the vicinity, i. e., one that obtains once per hour readings of temperature, dew point, and wind.

Relative humidity values should be calculated periodically from the temperature and dew-point measurements at the tower and from the weather airplane. The calculations should be based on standard meteorological tables (for example, tables 94 and 96 of reference 51). Three examples will illustrate the procedures.

Relative humidity, h_r , is defined as

$$h_r = (100 p_w) / p_{sat} \quad (12)$$

where p_w is the partial pressure of the water vapor (at the dew-point, or frost-point, temperature) and p_{sat} is the saturation vapor pressure of pure water over liquid water (at the ambient temperature) for a given sample of moist air at constant total barometric pressure.

Thus, if the air temperature T is 30°C , the dew point T_d is 20°C , and the air pressure is 1013.246 mb, we find, from the saturation vapor pressure tables,

$$\begin{aligned} h_r &= 100 (23.373/42.430) \\ &= 55.1 \text{ percent} \end{aligned} \quad (13)$$

If the air pressure had been other than 1013.246 mb, the vapor pressures would have had to have been changed accordingly. The relative humidity, however, would have been unchanged because both numerator and denominator would have changed by the same ratio.

If the dew point temperature is less than 0°C , the measurement is actually that of a frost-point temperature and the table for the saturation vapor pressure over ice must be used to find p_w . Thus, if $T = 10^{\circ}\text{C}$ and $T_d = -25^{\circ}\text{C}$,

$$\begin{aligned} h_r &= 100 (0.6323/12.272) \\ &= 5.2 \text{ percent.} \end{aligned} \quad (14)$$

If the air temperature is also less than 0°C , the value for p_{sat} is, by definition, taken as the vapor pressure over water (not ice) while p_w is for the frost-point temperature over ice. Thus, if $T = -10^{\circ}\text{C}$ and $T_d = -35^{\circ}\text{C}$,

$$\begin{aligned} h_r &= 100 (0.2233/2.8627) \\ &= 7.8 \text{ percent.} \end{aligned} \quad (15)$$

The tables of reference 51 give vapor pressures for temperatures in increments of 0.1°C . It should be feasible to examine the strip chart records and rapidly determine relative humidity values from the temperature and dew point measurements at the weather tower and in the weather airplane. The humidity data from the tethered radiosonde should be in terms of relative humidity directly. Relative humidity calculations should be performed after each flight of the weather airplane to keep the test crew aware of weather

conditions aloft. Similarly, the results of each ascent/descent probe by the tethered radiosonde should also be reported to the test director for evaluation and comparison. The strip chart records should be compiled and collected at the end of each test day as part of the test records.

RECOMMENDED TEST OPERATIONS

This section offers some remarks about special acoustical features of the airplane or engine/nacelle, describes recommended airplane flight operations, and presents a typical test matrix.

Airplane and Engine/Nacelle Configurations

If a test objective is to evaluate the acoustical effect of changing some component of the airplane or engine that generates significant noise or that could yield some noise reduction, then special precautions may be required. Changes to the airplane could involve flap modifications to increase lift or reduce drag. Engine nacelle changes could involve changes to or installation of acoustical linings in the inlet or discharge ducts. Separate-flow exhaust nozzles for turbofan engines could be replaced by common-flow nozzles with or without an internal mixer upstream of the final nozzle. An external jet noise suppressor nozzle could be installed.

For tests conducted to evaluate the acoustical effects of changes to an airplane or its engines or nacelles, experience has shown that it is desirable to have two airplanes available, a baseline and a modified airplane. Both airplanes should be of the same type with identical types of engines.

Comparison flight tests should be conducted on the same day, if at all possible, or within two or three days. Both airplanes will have to be equipped with the onboard digital data-recording system and the voice communication and time-correlation systems described in previous sections.

If costs prevent having more than one airplane available, the comparison flight tests should be run as close together in time as feasible on the same airplane.

Airplane Flight Operations

Each test day should begin and end with a coordination, planning, and review meeting conducted by the test director. Representatives from all the groups involved in the test program should attend the meetings. The main purpose of the meetings is to discuss problems that may hinder the test schedule and how best to resolve them.

The recommended test procedure is a series of nominally level passes over the array of microphones along the runway. Traffic permitting, the airplane should be flown in both directions over the runway to minimize the time between runs and to provide a measurement of atmospheric effects, if any, associated with sound propagation in winds of different directions as well as attitude and airspeed differences associated with headwinds and tailwinds. Care should be taken to minimize lateral deviations from the target flight path. (Note that references 25 and 52 contain the results of considerable experience with, and support for, level flights for flyover noise testing to achieve the specific objectives of USAF data acquisition and aircraft noise certification, respectively. Item 9 in Appendix A reviews the acoustical and aerodynamic problems associated with level-flight flyovers and describes some of the research needed to take full advantage of the potential savings in time and cost that level flyovers offer compared to normal (or simulated) takeoff and landing maneuvers.)

The configuration of the airplane to be used during the tests should be decided in advance. Wing leading-edge high-lift devices (slats, slots, or flaps) may or may not be deployed. Wing trailing-edge devices (flaps or flaperons) and landing gear will be used to adjust the drag of the airplane. The actual flap deflection angles should be checked (statically) to confirm that they are within the flap rigging tolerance limits specified by the airplane manufacturer.

Airplane flight attitude (pitch angle) will also be used to control drag and minimize airplane acceleration or deceleration during the pass. Airplane operating gross weight affects the airplane's lift (and hence the flow field around the airplane) and the engine power setting and, consequently, the noise level received by a microphone. An adequate supply of fuel should be onboard so that test delays for refueling are minimized. The airplane weight

also affects the allowable range of pitch angle and the magnitude of the change in airspeed to anticipate during each pass. For some aircraft, it may be desirable to include water ballast tanks in the fuselage to increase (or adjust) gross weight.

In determining target values for engine power settings, consideration should be given to the age of the engines, the number of operating hours since the last overhaul, and the total number of similar engines that are in service. Engine manufacturers provide engine performance data in terms of the performance of average (or mean) engines and an engine that meets minimal standards. If no valid data base exists, it is recommended that minimum engine performance data be used to establish inflight engine power settings. If there are a large number of comparable engines in service, and it has not been too long since the test engines were overhauled (especially for multiengine airplanes), then average engine performance data should be used. The differences between average and minimum performance will be most apparent at the highest engine power setting. The average engine will produce more thrust and more airplane acceleration than the minimum engine (for the same fuel flow rate), and will require a different airplane attitude. In any case, the operating characteristics of all installed engines should comply with the engine manufacturer's applicable criteria.

Target airspeeds will be different than normal takeoff or landing speeds. This result is inevitable since the flight paths are nominally level at nominally constant engine power settings. Passes at high engine power settings may be initiated at airspeeds less than normal takeoff speeds to allow for the acceleration that occurs. Conversely, passes at low engine power settings may be initiated at airspeeds greater than normal landing speeds to allow for the deceleration. In all cases, the target airspeed should be the airspeed when over the center microphone in the array of microphones under the flight path. The target height will also be that when over the center microphone. The test plan will include tests with different configurations and airspeeds (but same engine power setting) to help evaluate the magnitude of the configuration and airspeed effects. For each pass, however, the primary consideration should be to maintain height and engine power setting.

An adequate number of repeat runs should be planned. The functions of the repeat runs are to increase the statistical confidence level of the results; to provide an allowance for missed data points, lack of time synchronization, noticeable deviation from the flight track, height, or intended target conditions; and to permit detailed study of the reasons for scatter in nominally identical runs (conditions). Item 10 in Appendix A discusses some of the considerations involved in determining the number of repeat runs required for flyover noise testing.

Typical Test Matrix

Since a typical general test objective would be to obtain noise measurements over a range of engine power settings, airspeeds, and heights, a test plan might consider beginning with the test matrix of table 6 for one height H1. The total test would consist of 36 runs where runs 13 to 24 would be like runs 1 to 12 except at height H2 and runs 25 to 36 would be at height H3. Choices for H1, H2, and H3 might be 100, 300, and 1000 m; the actual values chosen would depend on the airplane, engines, and particular test objectives. The entire test, runs 1 to 36, probably could be accomplished in two days, airport traffic and weather permitting. If feasible, it would be desirable to repeat the entire test, runs 1 to 36, to obtain additional data.

The engine power settings P1 to P6 and corresponding airspeeds A1 to A6 might be chosen as follows:

P1 = maximum takeoff-rated referred thrust (no afterburning) for an air temperature of 15°C and a runway at sea level

P2 = hot-day takeoff-rated referred thrust for an air temperature of 40°C

P3 = 0.85 P1

P4 = 0.60 P1

P5 = 0.45 P1

P6 = 0.30 P1

TABLE 6. — TYPICAL TEST MATRIX

Run No.	Target height, m	Target engine power setting ^a $N_1/\sqrt{\theta_{t2}}$ or EPR ^b	Target indicated airspeed, $\text{m}\cdot\text{s}^{-1}$	Flight direction up or down runway
1	H1	P1	A1	up
2	H1	P1	A1	down
3	H1	P2	A2	up
4	H1	P2	A2	down
5	H1	P3	A3	up
6	H1	P3	A3	down
7	H1	P4	A4	up
8	H1	P4	A4	down
9	H1	P5	A5	up
10	H1	P5	A5	down
11	H1	P6	A6	up
12	H1	P6	A6	down

^afor all engines

^b $N_1/\sqrt{\theta_{t2}}$ is referred fan speed in percent of the design fan speed where N_1 is the rotational speed of the low-pressure section, $\theta_{t2} = T_{t2}/T_{\text{am, std}}$, T_{t2} = total temperature at the fan inlet in degrees kelvin, $T_{\text{am, std}} = 288.15^\circ$ kelvin.

EPR is engine pressure ratio and equals P_{t7}/P_{t2} where P_{t7} is the total absolute pressure at the discharge of the last turbine stage and P_{t2} is the total absolute pressure at the fan inlet.

Power settings P1 to P3 bracket the range of takeoff and climbout thrusts; P4 to P6 bracket the range of landing approach thrusts. A carpet plot of installed engine performance for various airplane Mach numbers, similar to the example shown in figure 16, should be obtained from the aircraft manufacturer for guidance in selecting the proper value of engine power setting corresponding to the desired value of inflight thrust.

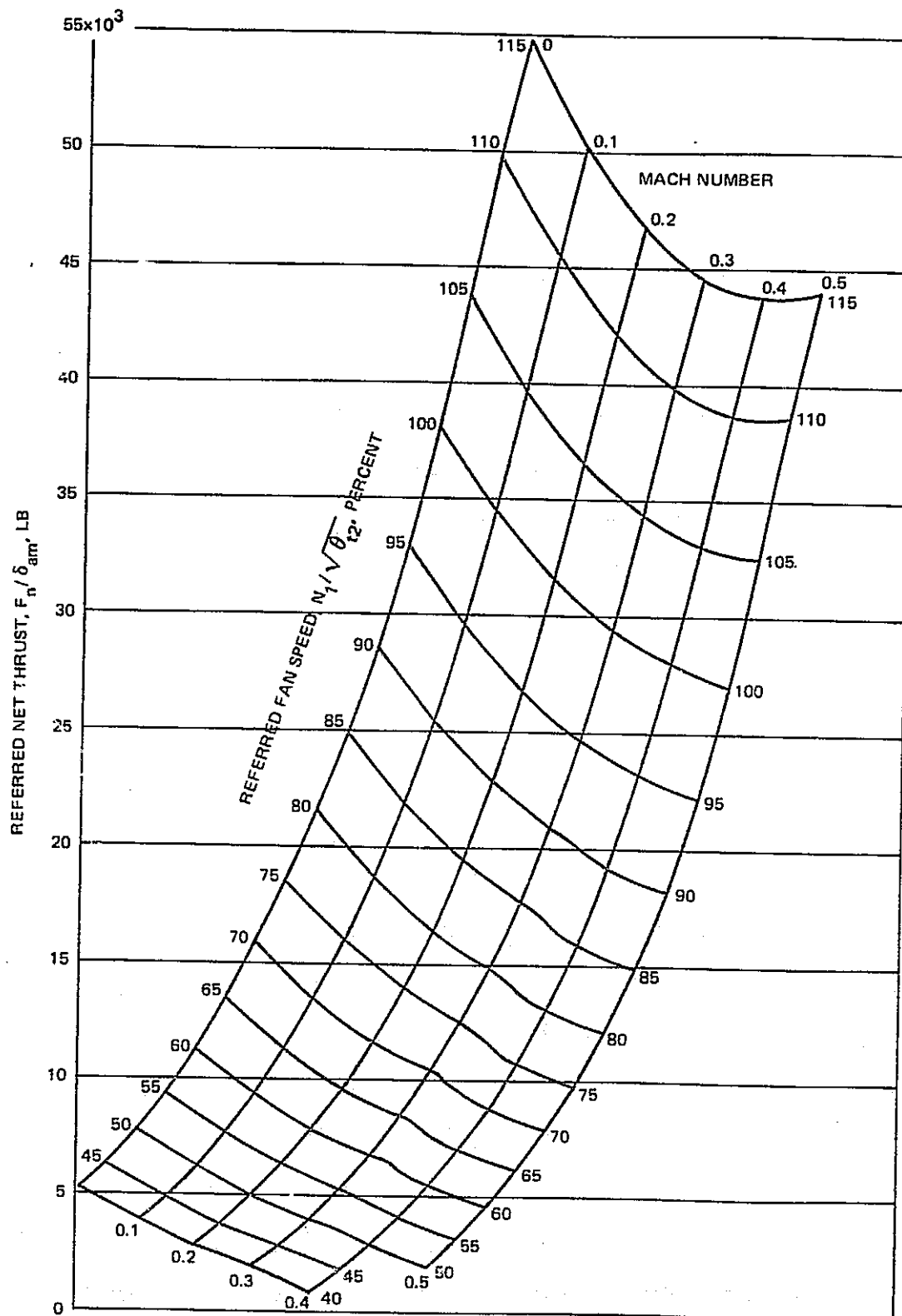


Figure 16. -Installed net thrust per engine as a function of airplane mach number and referred fan speed.

For all tests, the aircraft configuration will be selected by the flight crew appropriate to the situation. The operating gross weight will decrease as fuel is burned. Note that the proposed test plan could be used for some special tests, such as evaluation of a jet noise suppressor or a study of flight effects on engine noise, by using a three-engine airplane and flying with the center engine at power and the other two engines at flight or ground idle. The test plan, however, is not suitable for nonpropulsive noise tests where the flight paths will follow descending trajectories.

CONCLUDING REMARKS

Flyover noise measurement procedures have been reviewed. Specific procedures have been recommended that are applicable to subsonic transport-category aircraft using conventional means for generating lift and powered by turbojet or turbofan engines. The recommended procedures cover: test criteria, instrument performance requirements, data acquisition, and test operations.

Flyover noise data obtained according to the recommended procedures should be useful for a variety of purposes of the NASA Aircraft Noise Prediction Office, including development of generalized curves of various measures of noise level as a function of distance and engine power setting, verification of engine and airplane component noise-prediction procedures, and evaluation of noise-suppression designs.

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21 December 1976

APPENDIX A
RECOMMENDATIONS FOR AREAS OF NEEDED
RESEARCH WITH RESPECT TO AIRCRAFT
FLYOVER NOISE MEASUREMENT TECHNIQUES

Areas where additional research is needed with respect to flyover noise measurement techniques are in three categories: propagation effects, noise source(s), and testing procedures. Additional tests and analyses are needed to improve our understanding and the corresponding state of the art in all areas.

1. Atmospheric attenuation.--If the effects of varying meteorological conditions on the attenuation of aircraft noise were more thoroughly understood, it would mean that the extent of the allowable temperature/humidity envelope could be expanded, that more sites could be used for testing, that the number of days per year that a site could be used could be significantly increased, that fewer runs would be required, and that the quality of the results would be improved. The improved understanding should encompass the vertical and horizontal distributions of temperature and humidity as well as the changes of these distributions with time during a day. This improved understanding would then provide a means to properly assess the acoustical effects of nonuniform or unusual atmospheric absorption and thereby permit tests under a wider range of weather conditions than recommended in this report. The savings in time and cost would be substantial for both the aircraft industry and government agencies.

2. Large distances.--If a reliable method were available to account for atmospheric effects over long distances for a variety of weather conditions, then it should be feasible to conduct flyover noise tests at just one height over an array of microphones (say at 200 to 300 m) and extrapolate the results to much larger distances. The savings in test costs would be large. Large distances mean slant ranges at the time of closest approach that are on the order of 5000 m, including locations under and to the side of the flight path. The study of long-distance propagation is intimately related to the study of atmospheric attenuation (item 1). The study must also consider the changes in engine noise output and directivity that occur at different heights and airspeeds.

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3. Sideways propagation.—There apparently are a variety of effects associated with sideways propagation other than atmospheric effects. As the propagation angle becomes more shallow, the magnitude of the effects apparently increases. Furthermore, the type of the terrain over which the sound is propagating seems to play an important role. Atmospheric turbulence effects may be more important for sideways than overhead propagation. These effects influence the noise received by microphones to the side of a flight path and, at times other than overhead, for microphones located under the flight path. Sideways propagation effects also are important in determining the location or extent of noise level contours around an airport. An improved understanding of sideways propagation effects will help determine the number and location of side microphones.

4. Ground reflections.—Reflections from the ground surface influence the spectrum of the sound measured by a microphone at any height above the ground. The reflection effect depends on the acoustical impedance of the ground and on geometrical factors such as microphone height, airplane height, and sound wave incidence angle. An understanding of ground reflection effects would help to improve the understanding of sideways propagation problems. A better understanding of ground reflection effects would provide an improved means for selecting the height of the microphone above the surface. It would also provide a means of choosing or evaluating various types of ground terrain around the microphones. If field measurements of the acoustical impedance of the ground are required to evaluate ground reflection effects, the research should provide a practical means of determining the impedance and also of deciding where it should be measured since reflected sound waves impinge on the ground at many locations at various distances from the microphone.

5. Atmospheric turbulence.—Atmospheric turbulence affects the propagation of sound through the atmosphere. At the moment, however, the effects are not understood well enough to be able to specify any test criteria related to turbulence, nor what turbulence parameters should be measured, nor what to do with any turbulence data if it were to be measured. We do not know if a test conducted according to the meteorological test criteria recommended in this report will or will not encounter problems due to turbulence effects. Once turbulence effects are better understood it

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may be possible to be better able to explain some of the apparent scatter in the test results and thereby reduce, or eliminate, a number of repeat runs. The turbulence components should include not only those naturally occurring in the atmosphere but also turbulence induced by the passage of the aircraft (e.g., the wing tip vortices), especially for large airplanes.

6. Runway elevation.—The elevation of the runway above sea level affects the amount of acoustical power produced by the engines and the propagation of sound through the atmosphere. The magnitude of these effects is not known and an analytical procedure for quantifying them is not available. Many major airports are located at elevations well above sea level. A complete aircraft noise-prediction program should be able to account for differences due to runway elevation. Furthermore, there may be occasions when an available test site for flyover noise research tests is at an airport where the runway elevation is considerably greater than the elevation of runways used for previous tests. The results of tests of the same airplane and engines conducted at airports with significantly different runway elevations will not be comparable unless there is a standard procedure available to evaluate elevation effects on the sources of noise and on propagation.

7. Noise source location.—Most analyses of aircraft flyover noise measurements and most predictions of aircraft flyover noise levels assume that the airplane can be represented by a single equivalent acoustic point source. This assumption affects the analysis of propagation losses and adjustments from test to reference meteorological conditions. For large airplanes, the assumption is poor except at great distances. For airplanes with two wing-mounted engines and a third engine in the tail, the distance between the wing and tail engine (or time during a flyover at relatively small heights) can be quite significant. For airplanes with four wing-mounted engines, the distance between engines and the shielding effects can be significant for microphones located to the side of the flight path.

A proper definition of noise source location(s) is needed for each 1/3-octave band, for each instant of time during a flyover, and for microphones under or to the side of the flight path. For low-frequency jet noise, especially at high engine power settings, the proper location may be several equivalent nozzle diameters downstream of the engine exhaust nozzle. High-frequency noise may be jet noise or fan noise. Thus, the problem of locating

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noise sources is tied to definitions of the noise-generating mechanisms (in flight) as well as to methods of accounting for multiple-engine installations.

Definition of the noise source location affects the definition of acoustic path length and sound emission angle, quantities that are involved in the setting of test criteria and in test procedures as well as in data processing and analysis of the results. Acoustic propagation path lengths and sound-emission angles are usually determined with respect to some arbitrarily chosen reference point on the airplane. Identification of the locations of the sources of noise also impacts the prediction of aircraft noise from engine test stand data or engine component noise analyses.

8. Signal-to-noise ratio.--The signal-to-noise (S/N) ratio (or dynamic range) available from state-of-the-art instrumentation-grade multiple-channel analog tape recorders is barely adequate for the acquisition and processing of flyover noise data. With a 10-dB allowance for the high-amplitude peaks that are present in the random noise signals produced by jet airplanes, the available S/N ratio is only 35 to 40 dB. Because of the combination of attenuation of high-frequency signals by propagation effects and the natural high-frequency rolloff that characterizes the spectrum of many airplane noise sources, the S/N ratio really should be 70 to 100 dB rather than 35 to 40 dB. The result is that much of an aircraft's noise signal may be lost below the noise floor of the tape recorder.

The fact that the instrumentation's background noise floor represents relatively low equivalent sound pressure levels and that therefore the corresponding aircraft noise signals must represent even lower sound pressure levels should not deter the investigation of methods for improving S/N ratios, especially in the higher frequencies. The sound pressure levels that are lost below the background noise levels are values for test-day meteorological conditions. The values for reference-day meteorological conditions may well be considerably higher than those for test-day conditions. The complete reference-day spectra should be valuable not only for the spectral information, but also for the correspondingly higher values of calculated perceived noisiness (or some other measure of human annoyance).

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Research on ways to overcome the problem of inadequate S/N ratio is needed. Pre-emphasis (electrical boosting) of the signal before recording could be used but is not recommended because of other problems that are introduced. If propagation effects and long distance extrapolation procedures (items 1, 2, and 3 above) were understood and available, then all tests could be done at short distances where the signal strength was higher, assuming the problems of defining noise-source locations were resolved. (Indeed for future quieter airplanes, tests at short distances may be all that are feasible.)

Alternatively, it might be feasible to abandon FM analog recording and to obtain much higher S/N ratios by recording digital signals in the pulse code modulation (PCM) mode. Through multiplex techniques, the PCM mode also reduces the number of data tracks required to tape record a given number of microphone signals. PCM techniques, however require suitable high-frequency, high-speed analog-to-digital converters.

Another possibility for improving S/N ratio would be to abandon the tape recorder entirely and do on-line data processing in the field. This approach means that the data-processing requirements have to be well defined. There would be no opportunity for any other type of data analysis (for example, narrow fixed-bandwidth filters instead of 1/3-octave bands). Also there can be no more than one microphone unless several on-line data-processing systems are used. The various options need to be studied and evaluated.

9. Level flights.—The acoustical problems associated with level-flight passes need to be more thoroughly researched. There are several acoustical and aerodynamic differences between normal takeoffs and landings and level-flight flyovers. There is no procedure available to account for these effects. The lack of understanding reduces the confidence in projecting the results of level-flight tests to predictions of noise levels in communities around airports due to actual takeoff and landing operations.

In most every level-flight maneuver, it will be difficult to maintain a target airspeed, within a small tolerance band, for the required duration of the pass. The airplane will either accelerate or decelerate depending on the engine power setting and the number of engines operating. Furthermore, the

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airspeed will probably be significantly higher or lower than the corresponding takeoff and landing speeds. We need to understand the impact on noise generation and to develop procedures to account for the acceleration/deceleration and airspeed effects.

In attempting to maintain a constant height and near-constant airspeed, the pilot will adjust airplane pitch attitude, flap deflection, and the position of the landing gear. High nose-up attitude relative to the flight path will produce sound-pressure and time patterns that are different than they would be during actual takeoff or landing operations. Flying with a high nose-up attitude and with flaps extended and deflected may also produce significant shielding of forward-radiated noise from fuselage-mounted engines, shielding that would not be present during a normal climbout after takeoff.

There is a desire to use level flights instead of actual takeoff and landings because of the simplification in test procedures and the potential savings in test time and costs. To take full advantage of the level-flight technique, research is needed to explore the reasons for the acoustical differences and to develop reliable means of accounting for their effects.

10. Repeat runs.—At present, it is necessary to repeat a test several times with the same configuration and the same conditions to obtain a high degree of statistical confidence in the results. The issue is how many repeats are required and what is an acceptable confidence level. Reference 46 suggests four or five repeat runs for each engine power setting. References 17 and 18 require a minimum of six flights for a given test point. This report recommends a minimum of four runs (two up and two down the runway) for a given engine power setting and height.

If the aircraft noise signal can be considered to be generated by a stationary ergodic random process, then reference 46 (pp. 143 to 148) shows how to calculate the 90-percent confidence interval within which the true mean square sound pressure can be expected to be. The amount of uncertainty associated with any given sound pressure level depends on the bandwidth B of the filter and the sampling time t_s , i. e., on the number of statistical degrees of freedom m , where $m = 2Bt_s$, if the random process is gaussian with a so-called chi-squared distribution of the random variables.

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The greatest variability will be associated with the lowest frequency band since the data analyses will likely be performed using constant-percentage fractional-octave-band filters. For 1/3-octave-band filters, the bandwidth is about 23 percent of the center frequency. Thus, for the band with center frequency of 50 Hz, the bandwidth B is 11.5 Hz. If the sampling time t_s is 0.5 s, the number of degrees of freedom is $m = 2 \times 11.5 \times 0.5 = 11.5$.

From standard statistical tables for a chi-squared distribution, the ratio, for $m = 11.5$, of the estimate to the true mean square sound pressure will exceed $20.35/11.5 = 1.77$ with a probability of 5 percent and will fall below $4.90/11.5 = 0.43$ with a probability of 5 percent. Thus, in decibels, there is a 90-percent probability that the true mean will equal the estimate within limits given by $10 \log (1/0.43) = 3.7$ dB and $10 \log (1/1.77) = -2.5$ dB, or a spread of 6.2 dB. Since the bandwidth of the filters cannot be changed, reduction of the statistical uncertainty requires an increase of the sampling time t_s (increasing the number of degrees of freedom) or use of an ensemble averaging technique, assuming that several separate and statistically independent samples of the same noise signal can be obtained.

The difficulty of the problem here is compounded by the fact that the aircraft is moving and thus the noise signal is nonstationary by definition. The strength and directivity of the various noise sources can change rapidly within the duration of even a 0.5-s sampling interval. Therefore, lengthening the duration of the sampling time may not be feasible. Obtaining statistically independent samples for a wide range of sound-emission angles at several microphones also may be difficult to achieve because of the difficulty of maintaining constant airplane conditions for significant durations throughout a given flyover.

What is required is a procedure for determining an acceptable degree of confidence in each of the 1/3-octave-band sound pressure levels. Then, with allowance for experimental problems, a firm requirement for the minimum number of repeat runs can be logically established. The savings in time and cost could be substantial if fewer repeat runs were needed than are now considered necessary. On the other hand, if more repeat runs were required there would be a solid basis for the requirement.

APPENDIX B

PROCEDURE FOR ERECTING GUYED MICROPHONE TOWER

If guyed microphone towers are considered necessary, a procedure for erecting the towers could be the following.

Place a tower base (plywood footing and sole plate) such that the three vertices point to good locations for the soil anchors. Install the soil anchors such that the distance from the center of the tower will guarantee that the minimum guying angle is not less than 30° (0.58 times tower height). (Installation of a soil anchor is a two-man job.) Fix the tower base plate by driving six pegs into the ground around the perimeter of the base plate as shown in figure 7(a).

With the base plate and soil anchors in place, drive the trailer with the towers to a microphone location. Remove a tower. Lay the tower on the ground and bolt the base of the tower to the sole plate. Install guy wires to two soil anchors. Leave enough length for the guys to allow for slack and sag of the wire. Raise the top of the tower and support it temporarily on a sawhorse or similar support. Attach the microphone boom and brace with suitable bolts.

Attach the microphone clamp to the boom and the preamplifier to the clamp. Adjust the clamp so that the microphone orientation is that specified for the particular location. Attach the preamplifier cable to the boom and the tower and make the connection to the extension cable. Attach the microphone to the preamplifier and install the windscreen.

(It may be advisable to perform the initial acoustical and electrical calibration checks at this time. In this case, attach the extension cable to the microphone power supply and proceed with system checks assuming the microphone cables have been laid to the central recording station. If the cables are to be laid at a later time, then do not install the microphone and preamplifier until the microphone signal cable has been laid. Just erect the tower without the microphone and let it down to install and calibrate and then re-raise the tower.)

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Raise the tower by simply pulling on the free guy wire. Attach the third guy wire to the third soil anchor and adjust all guys until the three levels on the tower indicate that the tower is vertical. (Levels would not have to be permanently attached to the tower; a hand-held carpenter's spirit level would be satisfactory if the vertical was checked in at least three stations around the tower.) Once a tower is raised, it should be possible to lower and re-raise it in only a few minutes since the length of the guys should not need much, if any, readjustment.

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LABORATORY CALIBRATION EFFORTS TO SUPPORT FLYOVER NOISE TESTING

Nine different laboratory tests are required as follows for each data channel, except items (8) and (9), which relate to the data-processing system only.

(1) By comparison with a calibrated reference microphone system (microphone, preamplifier, and power supply calibrated and certified by the National Bureau of Standards or a commercial standards laboratory), determine the level, frequency, and waveshape of the output of the pistonphone acoustic calibrator. If the waveshape is distorted, determine the need to replace (or clean) the pistons. Check the operation of the pistonphone at the following three ambient temperatures: 0°, 20°, and 40°C. The output level should not be more than ± 0.1 dB different from the nominal output level.

(2) Determine the power spectrum level of the output voltage, at several values for the wideband output voltage, using a narrow-band spectrum analyzer over the frequency range from 20 to 20 000 Hz. The mean straight line through the power spectrum level data should be within ± 0.5 dB of a slope of -1 dB for a frequency increase by a factor of $2^{1/3}$. Also determine the root mean square value and amplitude probability distribution of the wideband output of the pink-noise generator at several output voltage levels.

(3) Again by comparison with a certified reference microphone system, determine the sensitivity of each microphone in dB re one volt per pascal at a single frequency such as 250 Hz in the flat portion of the microphone's amplitude frequency response. The sensitivity should be determined using the calibrated pistonphone that will be used in the field. The sensitivity value is not used directly in data processing since a reference sound level is recorded in the field. The main purposes of determining microphone sensitivity are to check against the manufacturer's sensitivity measurement, to obtain a history of sensitivity data, and to provide traceability to the certification of the National Bureau of Standards. If sudden sensitivity changes of more than 0.2 dB occur, the microphone should be returned to the manufacturer or a standards laboratory for inspection and calibration.

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(4) Determine the pressure response of each microphone and of the certified reference microphone over the frequency range from 45 to 11 200 Hz. An electrostatic actuator may be used instead of the closed coupler reciprocity method to determine pressure response. The free field correction factors to be used for each microphone are then determined from (a) the free field response of the reference microphone (accomplished by the National Bureau of Standards, or a Standards Laboratory, at normal (0 deg) incidence over the same frequency range), (b) the difference in pressure response between that of the reference microphone and the test microphone, and (c) the manufacturer's free-field correction curves for the microphone as a function of angle of incidence and frequency.

(5) Determine the accuracy of all steps on each attenuator in the data-acquisition system. The actual gain change should be within ± 0.1 dB of the nominal gain change.

(6) Using a special insert voltage device available from the microphone manufacturer which has a resistor in series with a capacitor whose capacitance equals the nominal capacitance of the microphone, determine the linearity of the complete data-acquisition/data-processing system. The linearity calibration should be accomplished by recording a pink-noise signal from the calibrated pink-noise generator at the maximum record level. Then, using the calibrated step attenuators on the recorder input signal-conditioning amplifiers, record again the pink-noise signal at record levels that are 10, 20, 30, 40 (and preferably 50) decibels below the maximum record level. For each 1/3-octave band from 50 to 10 000 Hz, the best fit to the set of equivalent sound pressure levels and attenuator settings should not deviate from a straight line by more than 0.5 dB over a range of at least 40 dB.

(7) Determine the dynamic range of the complete system using the same special insert voltage device as above. Record the output of the pink-noise generator at the standard record level (10 dB below the maximum record level) followed by a 30-s recording with the generator switched off but still connected to the insert voltage device. On playback, adjust the gain of the reproduce amplifier to give a wideband output voltage equal to the wideband input voltage corresponding to the maximum record level (i.e., 1 V rms). In each 1/3-octave band from 50 to 10 000 Hz, the level of the background noise

APPENDIX C

(generator off) should be at least 45 dB less than with the pink noise present. A dynamic range of 50 dB is preferred for each band.

(8) Determine correction factors for each of the twenty four $1/3$ -octave-band filters to account for the nonideal frequency response of the filters. Use the procedures specified in reference 53. Evaluate the correction factors by criteria specified for the data-processing system.

(9) Determine the averaging characteristics of the detector/integrator used in the data-processing system. Record a wideband white noise signal on any data channel at the standard record level. Evaluate the detector/integrator in each of the twenty four $1/3$ -octave-bands using procedures and performance criteria specified for the data-processing system.

(Note that the results of the tests done for items (8) and (9) should not change with time and therefore the tests need be done only once unless something is changed in the data-processing system that affects the filters or the detector/integrator. Note also that frequency and incidence response of the windscreens, as a function of wind speed and wind direction, have to be determined in a laboratory.)

APPENDIX D

SYMBOLS

A1 to A6	airspeeds (table 6), $m \cdot s^{-1}$
AMRL	Aerospace Medical Research Laboratory
ANOPO	Aircraft Noise Prediction Office
ANOPP	Aircraft Noise Prediction Program
ANSI	American National Standards Institute
B	bandwidth of filter, Hz
BBN	Bolt Beranek and Newman Inc.
C	celsius
EPA	Environmental Protection Agency
EPR	engine pressure ratio, P_{t7}/P_{t2}
F	fahrenheit
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FM	frequency modulation
F_n	net thrust, N
F_n/δ_{am}	referred net thrust, N
H	airplane height, m
H1 to H3	airplane heights (table 6), m
Hz	hertz
ICAO	International Civil Aviation Organization
IRIG	Inter-Range Instrumentation Group
$\Delta L_{B, meas}$	propagation loss caused by atmospheric absorption, in a 1/3-octave band, under measured meteorological conditions, dB
$\Delta L_{B, ref}$	propagation loss caused by atmospheric absorption, in a 1/3-octave band, under reference meteorological conditions, dB
L_p	sound pressure level, dB
$L_{p, adj}$	adjusted sound pressure level, dB
$L_{p, meas}$	measured sound pressure level, dB
M_a	airplane Mach number, V_a/c
N_1	fan shaft speed, rpm (or percent)
$N_1/\sqrt{\theta_{t2}}$	referred fan shaft speed, rpm (or percent)
NEF	Noise Exposure Forecast

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P1 to P6	engine power settings, (table 6)
P _{am}	ambient pressure, N·m ⁻²
P _{am, std}	standard ambient pressure, 1.01325 x 10 ⁵ N·m ⁻²
P _{t2}	total absolute pressure at the fan or engine inlet, N·m ⁻²
P _{t7}	total absolute pressure at the discharge of the last turbine stage, N·m ⁻²
PCM	pulse code modulation
SAE	Society of Automotive Engineers
S/N	signal-to-noise ratio
T	air temperature, degrees kelvin (or celsius)
T _{am, std}	standard ambient temperature, 288.15 degrees kelvin
T _d	dew point temperature, degrees kelvin (or celsius)
T _{t2}	total temperature at the fan or engine inlet, degrees kelvin
V _a	airspeed, m·s ⁻¹
a	atmospheric absorption coefficient, dB·m ⁻¹
a _i	atmospheric absorption coefficient in the ith layer of the atmosphere, dB·m ⁻¹
a _{ref}	atmospheric absorption coefficient for reference meteorological conditions, dB·m ⁻¹
ac	alternating current
c	speed of sound, m·s ⁻¹
d	propagation path length, m
d _i	propagation path length in the ith layer of the atmosphere, m
dB	decibel
dc	direct current
f	frequency, Hz
f ₁ , f ₂	lower and upper cutoff frequency defining the significant transmission of 1/3-octave-band filters, Hz
h _r	relative humidity, percent
P _{meas}	measured mean-square sound pressure at the receiver microphone, (N·m ⁻²) ²
P _w	partial pressure of water vapor, N·m ⁻² (or millibars)
P _{sat}	saturation vapor pressure of pure water over liquid water, N·m ⁻² (or millibars)
μPa	micropascal
Δr	difference between reflected path length and direct path length, m
rms	root mean square
rpm	revolutions per minute

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t	time, s
t_s	sampling time, s
x	length coordinate along the extended runway centerline, m
y	lateral deviation coordinate in the ground plane and perpendicular to the extended runway centerline, m
z	height coordinate above the extended runway centerline, m
α_{meas}	pure tone atmospheric absorption constant for the measured meteorological conditions, nepers $\cdot$ m $^{-1}$
α_{ref}	pure tone atmospheric absorption constant for reference meteorological conditions, nepers $\cdot$ m $^{-1}$
δ_{am}	reference pressure ratio $P_{\text{am}}/P_{\text{am, std}}$
θ	sound emission angle, radians (or degrees)
θ_{t2}	reference temperature ratio $T_{t2}/T_{\text{am, std}}$
λ	wavelength, m
ξ	coordinate along a propagation path from the receiver point to the source point or from the source point to the receiver point, m
ξ_r	coordinate of the receiver point, m
ξ_s	coordinate of the source point, m
τ	nondimensional power transmissibility function for the frequency response of a filter
ψ	airplane position angle, radians (or degrees)

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